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Best Practices:

Photovoltaic Stormwater Management Research and Testing (PV-SMaRT)

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ACKNOWLEDGEMENTS

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Introduction

Stormwater management practices, permitting, and regulation do not account for the unique characteristics of large-scale photovoltaic (PV) installations.[1]

Stormwater standards were implemented to administer the Clean Water Act and are intended to protect surface waters and groundwaters from the effects of land development.[2] Development changes stormwater flow and groundwater infiltration from what occurs in an undeveloped or natural landscape. Removing native vegetation or increasing the amount of impervious surface (roofs, parking, streets) in a watershed significantly changes how the watershed functions. Increased surface flow and decreased infiltration result in greater amounts of pollutants and sediment flowing into rivers and lakes, greater soil erosion, and impairment of our surface waters.

The primary predictor of water quality degradation from development is the amount of impervious surface; more impervious surface is proportional to more degradation.

Solar development land change can differ considerably in form from other types of residential and commercial development practices. Solar panels can have vegetated areas (pervious) underneath the panels and large areas of vegetated soil between and around the arrays.

Permitting standards and processes based on impervious surface impacts can therefore be unpredictably variable for solar development, both increasing development costs (soft costs and infrastructure costs to mitigate modeled stormwater runoff) and diminishing water quality outcomes by not taking advantage of "green infrastructure" on solar development sites.

Why PV-SMaRT?

The Photovoltaic Stormwater Management Research and Testing (PV-SMaRT) project developed and disseminated research-based, PV-specific tools and best practices for stormwater management and water quality at ground-mounted PV sites. The project used five ground-mounted PV sites in the United States to study stormwater infiltration and runoff. These sites represent a range of elevations, slopes, soil types, and geographical locations. The unique conditions at each site were characterized, and measurements were taken of soil infiltration, runoff, site vegetation density, speciation and rooting depth, precipitation, and drip edge runoff. As a result of the research and hydrological modeling conducted, the PV-SMaRT project developed an easy-to use calculator to estimate stormwater runoff from ground-mounted PV arrays. To learn more about the project visit https://www.nrel.gov/solar/market-research-analysis/pv-smart.html.

Identifying the solar development gaps in existing stormwater permitting and regulatory processes offers an opportunity to increase consistency and transparency of water quality permitting and reduce solar development costs and permitting barriers. The PV-SMaRT field research and modeling provides the data-driven foundation to answer water quality questions based on real-world measurements at five solar sites across the country. This foundation includes the following:

- identifying the key design impacts of solar development that affect stormwater management and water quality outcomes
- creating solar-specific runoff coefficients
- describing best practices that reduce permitting uncertainty, limit unnecessary infrastructure investment, and improve water quality outcomes

1 PV-SMaRT Potential Stormwater Barriers and Opportunities, Great Plains Institute, 2021, describes the survey of existing stormwater and water quality practices across the nation, and the gaps in existing regulatory processes associated with groundmounted solar development.

2 Agricultural activities also affect surface flow and infiltration, but are exempt from CWA regulation (Section 404(f)(1)).

The PV-SMaRT field testing and modeling identified four key elements of solar development that have a large impact on managing stormwater and improving water quality outcomes:

1. Compaction—Managing soil compaction and bulk density across the site
2. Soil depth—Including soil depth (rooting depth) in stormwater modeling and design
3. Ground cover—Installing, establishing, and maintaining appropriate vegetated ground cover between and under the arrays to facilitate infiltration
4. Disconnection—Ensuring appropriate distance between arrays for infiltration

The PV-SMaRT research findings demonstrate that additional stormwater infrastructure may not be needed under ideal site conditions and site design for water quality, even for 100-year frequency design storms. When best practices are not followed, significant additional stormwater management may be needed. The research findings also demonstrate that runoff estimates are, on average, 38 percent lower using PV-SMaRT methods relative to the Natural Resources Conservation Service runoff curve number method for a 100-year storm. Overestimating runoff can have a cost impact on solar projects which would need more land or additional best management practices.

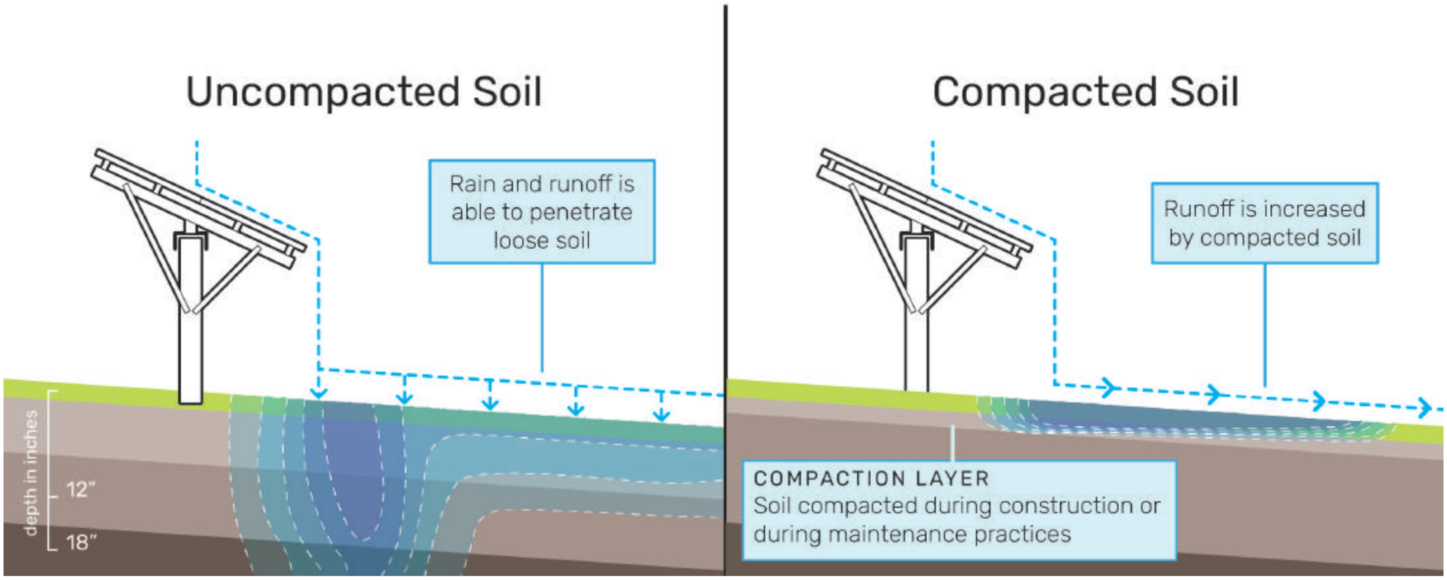
The following fact sheets, one for each of the four elements, describe (1) the typical gaps in stormwater permitting processes at the state or local level that could be addressed to incorporate the research findings of that element and create a more predictable and transparent permitting process with improved water quality outcomes; and (2) a portfolio of solar project best practices to address stormwater management and improve water quality outcomes associated with that element.

The portfolio of best practices in each fact sheet should not be interpreted as requirements. Rather, the best practices are a set of siting and site design options that allow the solar site to act as green infrastructure or indicate circumstances when additional stormwater and water quality controls will be needed.

The PV-SMaRT program developed an easy-to-use stormwater runoff calculator, which can be freely downloaded at https://license.umn.edu/product/pv-smart-solar-runoff-calculator. The calculator allows users to estimate runoff amounts for specific types of conditions. The calculator also allows users to identify a solar- and site-specific curve number to incorporate into other models and incorporates the project findings validated with real-world measurements. The site also includes a user manual to guide users to correct and productive use of the calculator.

Photo by David Mulla

Soil moisture and infiltration field testing conducted by the PV-SMaRT team.



Finding #1:

Compaction/Bulk Density

Compacted soils limit stormwater infiltration, and highly compacted soils act like impervious surface in creating runoff. The PV-SMaRT modeling results demonstrated that compaction is the most important consideration in determining stormwater runoff. Having compacted soil between the arrays increased runoff, on average, by almost 100%. Modeling results indicated that target bulk densities should be within 1.1- 1.5 g/cm3, depending on the soil classification or texture, to minimize runoff.

Large vegetated areas are a unique water quality asset in solar development, but the asset is greatly diminished if soils are compacted. Tighter soils (more clay and finer grains, having an inherent higher bulk density) are particularly subject to problems associated with compaction. While soil texture is an unchangeable site characteristic, low impact development practices or careful mitigation of compacting activities can reduce bulk density and significantly increase infiltration.

Soil compaction frequently occurs during development from heavy equipment driving over the site in the construction process, and sometimes from deliberate compaction to stabilize foundations or pilings. Soil compaction can also occur post-construction from maintenance activities. Highly managed sites where topsoil is removed, the site is heavily graded, or cut-to-fill excavation is used have a high likelihood of compaction requiring mitigation to achieve appropriate bulk densities.

Soils that are not compacted allow much greater infiltration. Looser soils also allow improved and more rapid vegetative establishment (which then, if deep-rooted ground cover is used, helps maintain lower bulk densities).

Compaction is measured by bulk density. Measuring is straightforward and reliable, provided the measurement is made with dry soils. The PV-SMaRT field research sites included sites with all classes of soil (A through D) but had been managed for low to medium bulk densities that significantly improved runoff relative to higher bulk densities.

Best practices and barriers or gaps in existing regulatory processes are noted below.

Permitting Barriers and Gaps

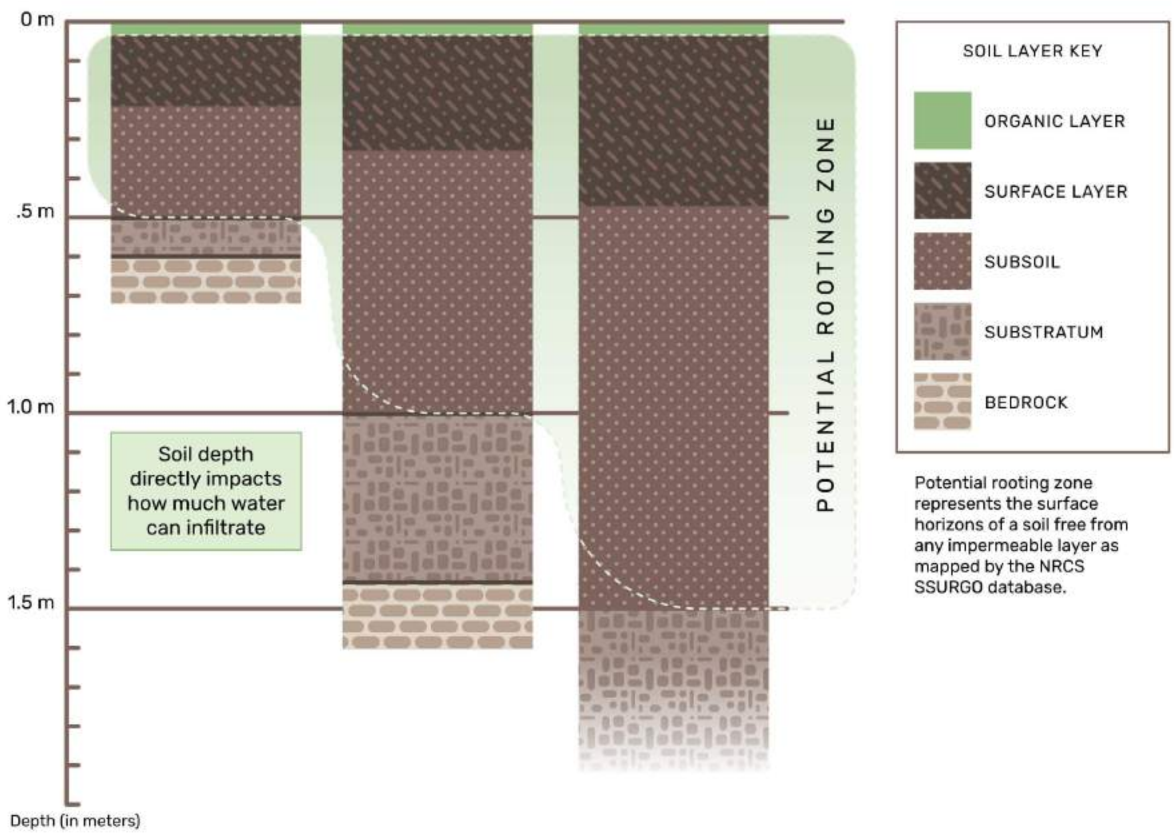
Most stormwater permitting practices do not include measurements of bulk density nor recognition of the critical role that bulk density plays in creating disconnection opportunities. Low-impact construction practices for reducing soil compaction or decompaction after construction are sometimes recommended in best practices. Still, few permitting authorities set bulk density targets for final stabilization or recognize the water quality benefits of establishing and maintaining low post-construction bulk density.

Current Practice	Addressing Current Practice Gaps
Compaction is not measured, monitored (pre-or post-construction), or included in standards.	Bulk density can be measured using a bulk density sampler, consistent with USDA NRCS recommendation.
Most permitting processes do not capture or prioritize the infiltrative capacity of low bulk density soils.	Sites with low bulk density (and adequate soil depth) can have infiltrative capacity in excess of minimum infiltration standards. The PV-SMaRT solar runoff calculator can be used to understand the infiltrative capacity of the site.
Low-impact development (LID) construction techniques that affect compaction are generally not included in the Stormwater Pollution Prevention Plan (SWPPP).	LID construction practices can increase the certainty of post-construction desired outcomes. Practices include minimal grading, maintaining existing established vegetative cover, no removal of topsoil, post-construction decompaction, etc.
Inconsistent (across jurisdictions) treatment of post-construction bulk density and decompaction/ compaction avoidance.	LID construction practices can increase the certainty of post-construction desired outcomes. Practices include minimal grading, maintaining existing established vegetative cover, no removal of topsoil, post-construction decompaction, etc.

Project Best Practices for Water Quality

In regard to planning for stormwater runoff and affecting water quality measurements in receiving waters for solar projects, compaction of soils (measured by bulk density) is the single most significant element. Developers, site managers, and engineering, procurement, and construction companies should consider the following portfolio of best practices to reduce bulk density and maximize infiltration on-site for the life of the project.

Stormwater Best Practices	Description
Consider soil bulk density ramifications in site design.	Compaction/bulk density issues are the most significant factor in managing stormwater and meeting state or host community water quality goals. Consider modifications to standard site design (array layout, vegetation selection, final stabilization procedures) to reduce bulk density, particularly for sites with finer soils.
Set and confirm post-construction soil bulk density standards for EPCs and other contractors.	• Measure soil bulk density before and after construction, both between arrays and under arrays. • Identify compaction or bulk density standards for contractors to allow them to integrate consideration of compaction into construction practices. • Post-construction, if bulk density is high, decompact areas between arrays to a minimum of six inches and under arrays to a minimum of four inches.
Use LID construction techniques and mitigate for soil compaction from construction activities.	• Minimize grading to the extent practical, and select pile and array systems that require less or no grading. • During construction, stage or limit use of heavy equipment to specific areas to limit soil compaction and plan for post-construction decompaction as needed. • Prevent soil removal except for remediation. • Maximize the preservation of pre-construction vegetation. • Seed the site prior to construction activities.
Take a green infrastructure approach in siting, site design, and modeling to capture opportunities for water quality or watershed function improvements.	• Include a post-construction vegetation establishment and maintenance plan in Stormwater Pollution Prevention Plan for implementation by site owners/managers. • Use appropriate deep-rooted vegetative cover between and under the array that lowers bulk density, increases infiltrative capacity, and reduces the need for vegetative maintenance over the life of the project.



Finding #2:

Soil Depth

The soil depth, also known as rooting depth, defines the capacity of the site to infiltrate water. Soil depth measures from the soil surface to the first impervious layer past which water (and roots) cannot infiltrate. Soil depth in the modeling ranged from 0.5 to 1.5 meters, with deeper depths possible, but modeling showed little impact beyond 1.5 meters. Soil depth is the second most important element of the site in terms of stormwater management and water quality risk or opportunity. The PV-SMaRT research estimated a 78 percent increase in runoff as soil depth decreases from 1.5 to 0.5 meters.

Soil depth cannot be easily improved on a site, as the impervious layer would have to be plowed or broken through or additional soil added to the site. Soil depth can, however, be diminished in some development scenarios, where extensive grading, soil removal, or cut-and-fill techniques alter the rooting depth of the site. Solar projects currently evaluate soil depth from the standpoint of engineering the pile system to support the arrays but not in evaluating infiltrative capacity.

Considering the infiltrative capacity of the site would be a new concept for most permitting processes. Such a measure would contribute to evaluating sites as green infrastructure for watershed benefit. The PV-SMaRT runoff calculator incorporates soil depth into the design storm runoff estimates or site-specific curve numbers.

Best practices and barriers or gaps in existing regulatory processes are noted below.

Permitting Barriers and Gaps

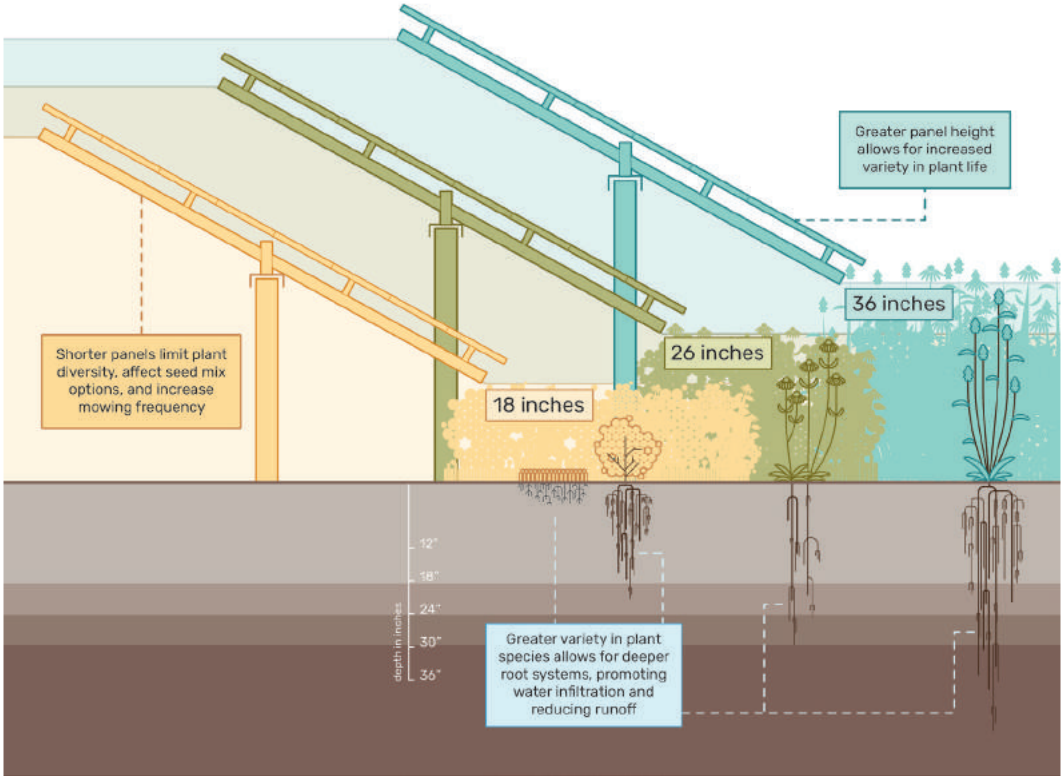
PV-SMaRT examination of existing permitting practices and standards found no examples of permitting processes that considered soil depth in evaluating stormwater risk or the need for stormwater infrastructure. As deeper soil depths allow for a much greater capacity to absorb stormwater, recognition of this capacity could significantly change the need for engineered stormwater infrastructure. Soil depth also significantly affects the opportunity of using the solar site as green infrastructure in watersheds of impaired waters or in water quality trading regimes.

Current Practice	Addressing Current Practice Gaps
Current permits or permit coverage do not require measurement or consideration of soil root depth.	Measure pre-construction soil/rooting depth in site assessments and post-construction soil depth to use in stormwater modeling and runoff prediction.
Soil depth and infiltrative capacity are not accounted for in stormwater manuals that guide local permit officials and permittees.	Update stormwater manuals to guide local officials and permittees consistent with research findings.
There are inconsistent permit requirements and parameters across different jurisdictions.	Utilize validated PV-SMaRT calculator for establishing runoff curve coefficients based on field parameters that include soil depth.
Local permitting practices do not consider the importance of rooting soil depth on solar projects.	• Provide training on the scientific solar-specific considerations of site infiltrative capacity. • Develop statewide guidance on soil depth and opportunities/ considerations for water quality permits or standards. • Develop case study examples to resolve uncertainty and increase comfort on the impacts of large-scale solar.
Local and state permitting practices do not recognize the green infrastructure opportunities afforded by sites with high levels of infiltrative capacity.	Local and state water quality standards frequently prioritize green infrastructure recommendations over gray infrastructure best management practices (BMPs). Soil depth can be an asset that helps meet local protection requirements, total maximum daily loads (TMDLs) and other water quality goals.

Project Best Practices for Water Quality

Most solar projects already evaluate soil depth from the standpoint of engineering the pile system or racking to support the arrays but not in evaluating the infiltrative capacity of the site. Stormwater modeling that incorporates soil depth provides a more accurate measure of runoff compared to typical practices and, if utilized as a stormwater control feature, can reduce the need for other infrastructure. For sites with shallow soil depth, understanding the need for additional mitigation will prevent post-construction problems and expensive retrofits.

Best Practice	Description
Practice site design for disconnection that reflects post-construction soil depth.	Incorporate the site's pre- and post-construction infiltration capacity into array layout and design. Deeper soil/rooting depth is a natural asset. Shallower soils (or heavily graded sites) are a site limitation, likely calling for additional retention, larger disconnection areas, or other designs.
Incorporate soil depth into stormwater and water quality modeling.	Soil/rooting depth indicates the infiltrative capacity of the site. Deeper depths are an asset, and shallower depths indicate a need for additional BMPs.
Adopt solar-specific mitigation of runoff under special (more challenging) site conditions.	The site's infiltrative capacity can be an asset to manage stormwater on more challenging sites—steep slopes, clay or dense soils, or conversion of forested land covers—if incorporated during the design process.
Use LID construction techniques to protect existing watershed function and the infiltrative capacity of the site.	• Minimize or eliminate grading of the site. Grading can significantly affect the infiltrative capacity of the site and result in the need for additional engineered stormwater BMPs. • Prevent soil removal. Topsoil and rooting soils enable infiltration. Removing soils will increase the need for engineered BMPs.
Look beyond the design storm and meeting minimum standards.	Soil depth is a site asset that can provide host community water quality benefits, particularly in watersheds with agricultural land uses or impaired surface waters. Documenting the potential benefits could make permitting processes more transparent.



Finding #3:

Ground Cover

The choice of ground cover, from bare earth and gravel to fully established native grassland or pollinator habitat, has the third highest effect on stormwater runoff. The PV-SMaRT research noted a significant increase in stormwater runoff, as much as 38 percent, for vegetation with shallow roots or intermittent density (such as poorly managed row crop or mowed turf grass) compared to well-established prairie or other deep-rooted perennials.

The choice of vegetated ground cover has an interactive effect with bulk density, particularly for deep-rooted native vegetation that increases the space between soil particles to lower bulk density and provide a path for water infiltration. The water quality effect of deep-rooted ground covers is rarely incorporated in existing regulatory or permitting frameworks.

Additional co-benefits are provided to host communities from pollinator or related ground covers, such as the creation or restoration of habitat, improvement of visual impacts, or pollinator services to adjacent agriculture. Such co-benefits are frequently the primary interest in such site design.

A number of site design decisions affect the post-construction sustainability of ground cover choices for both project economics and water quality and ecosystem functionality. The portfolio of best practices requires attention to tradeoffs between capital and operating expenditures and is affected by regulatory pathways. Most stormwater permits require 70 percent coverage 1-2 years after development, and this is often not possible with deep-rooting, native vegetation plant species.

Best practices and barriers or gaps in existing regulatory processes are noted below.

Permitting Barriers and Gaps

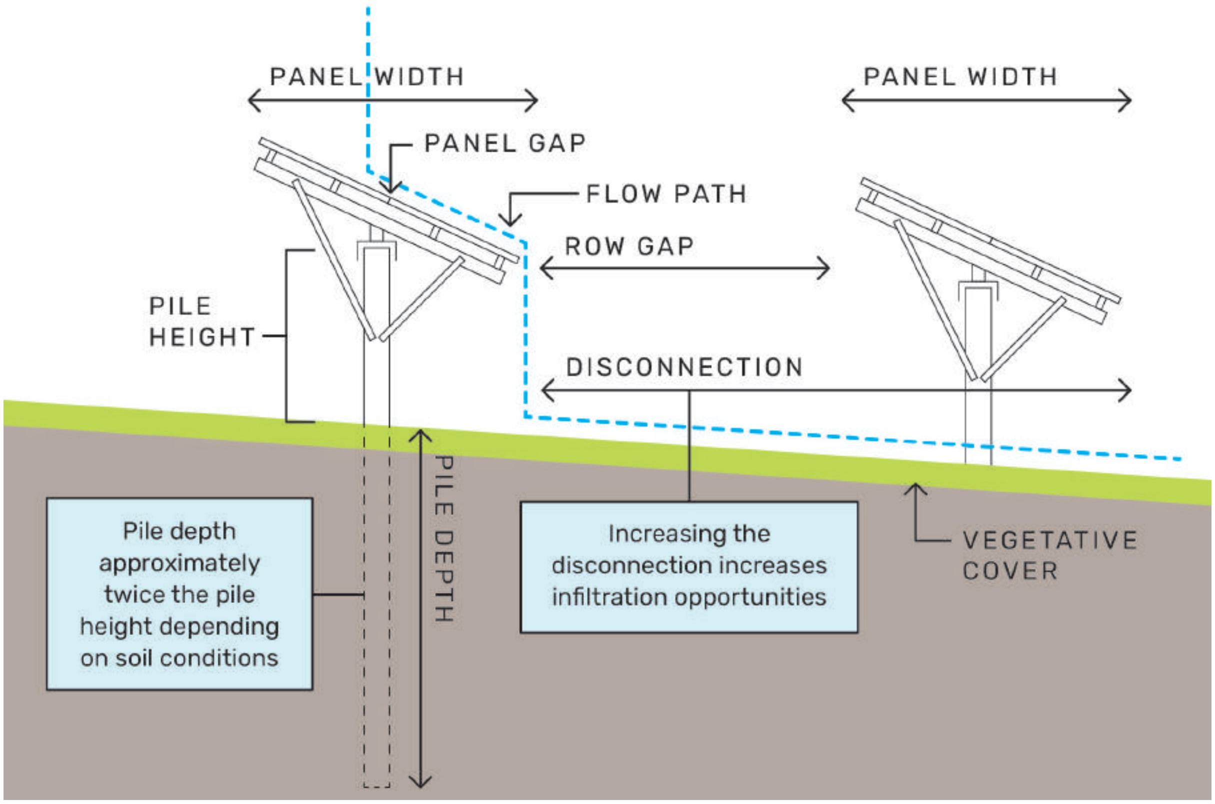
PV-SMaRT review of existing permitting practices found that the water quality benefits of deep-rooted ground covers are rarely incorporated in regulatory or permitting frameworks. The PV-SMaRT runoff calculator does take ground cover differences into consideration and allows regulators to account for the benefits of native or deep-rooted perennial ground covers in meeting design storm or water quality standards. In addition, final stabilization typically requires the full establishment of permanent vegetative cover, a standard that can take significantly longer for preferred (from a water quality perspective) ground covers. Some states and local jurisdictions have addressed this issue by allowing for alternative forms of stabilization, such as cover crops that allow permanent vegetation to establish.

Current Practice	Addressing Current Practice Gaps
Different ground covers have different runoff coefficients that are not accounted for in permits.	Use the PV-SMaRT solar runoff calculator or equivalent tool based on solar-specific field research to evaluate the efficacy of different ground covers given the other site characteristics.
Barriers exist for co-benefit/multi-benefit ground covers in the construction stormwater permit.	• Modify construction general permit final stabilization pathways or an accompanying guidance document that allows habitat- and pollinator-friendly or native ground cover to reach final stabilization in the same time frame as turf or other stabilization methods. • Create a plan for the establishment of native or naturalized optimal vegetative cover that allows interim use of an appropriate cover crop.
Local permitting practices do not consider the water quality benefits and risks for different ground cover on solar projects.	• Train on the science behind water quality benefits of different ground covers. • Consider statewide guidance or case studies on ground cover benefits at solar facilities for different permits (TMDLs, Municipal Separate Storm Sewer Systems, Section 404 or equivalent state standards, etc.).

Project Best Practices for Water Quality

Most solar development projects rely on fast establishing fescues or other turf grasses as the final vegetative ground cover. These ground covers typically have significantly shallower root systems that do not provide the same infiltrative benefits as deep-rooted natives or pollinator mixes and require more frequent mowing than established pollinator or similar ground covers. Native or pollinator seed mixes are, however, more expensive. The benefits of native or deep-rooted perennial in water quality performance, improved visual impact, creation or enhancement of local habitat, lowered maintenance costs, and pollination service for surrounding agriculture must be weighed against the higher initial costs of such systems. If appropriately addressed in stormwater modeling, pollinator and similar ground covers can avoid capital costs of additional or larger capacity stormwater infrastructure. PV-SMaRT modeling shows that in some cases no additional stormwater controls are needed other than the pollinator ground cover.

Best Practice	**Description**
Use array designs that sustain vegetative cover and infiltration.	• Consider racking system height that affects vegetation cost, effectiveness in infiltration, and diversity of an ecosystem, both under and between arrays. • Consider how the array layout/design affects the ease of post-construction maintenance. • Consider the interaction between vegetation management and the use of bifacial panels.
Take a green infrastructure approach to site design and selection of ground covers and post-construction maintenance practices.	• Use habitat- or pollinator-friendly solar standards where available (currently available in 12 states) or similar deep-rooted vegetative ground covers. • Include a post-construction vegetation establishment and maintenance plan in Stormwater Pollution Prevention Plan. • Incorporate the staged use of compatible cover crop with the final vegetative mix to bridge the time between the end of construction and establishment of final vegetative cover. • Use appropriate vegetative cover under the array that can be self-sustaining and sufficient to maintain the vegetative root system and infiltrative capacity.



Finding #4:

Disconnection

The space under and between arrays can be designed and maintained to create infiltration area to disconnect impervious surfaces from receiving water bodies. Disconnecting impervious surfaces from drainage systems and surface waters is what distinguishes solar development from other kinds of development. For disconnection to mitigate water quality risks, the disconnected area must be able to infiltrate water quickly and reliably (compaction/bulk density and deep-rooted ground cover), have volumetric capacity to hold a design storm (soil depth), and must have sufficient vegetated cover to both improve and slow sheet flow (ground cover).

The PV-SMaRT research identified the distance between arrays as an important element for managing stormwater. Runoff increased by 14% for an array spacing of 15 feet (piling to piling) versus 35 feet.

Array placement is generally guided by shading considerations (to prevent one array from shading the adjacent array). Arrays examined in the study had a spacing of 25 feet, which was sufficient disconnection area to infiltrate most design storms. For sites with tight soils, greater compaction, or steep slopes, increasing the disconnection between arrays can help mitigate these conditions.

Most existing permitting practices only indirectly address disconnection as stormwater mitigation strategy. As disconnection is an existing accepted best practice, the regulatory gap can be easily addressed.

Best practices and barriers or gaps in existing regulatory processes are noted below.

Permitting Barriers and Gaps

Existing permitting practices typically only indirectly address disconnection as a stormwater mitigation strategy for solar projects. While disconnection is an accepted best practice in many stormwater manuals for other forms of development, the magnitude of disconnection opportunity for solar projects is quite a bit larger than most other forms of development.

Disconnection is allowed as a mitigation tool in some jurisdictions that have developed solar-specific stormwater guidelines, with recognition of the areas between and under the arrays as infiltration areas. Generally, those standards specify a minimum distance between arrays in order for disconnection to be used as a BMP. Stormwater modeling frequently does incorporate the effects of disconnection on runoff but generally does not treat disconnection as a BMP.

Current Practice	Addressing Current Practice Gaps
Uncompacted areas in between the arrays are often wrongly classified as impervious surfaces, which is reflected in field observations and modeling.	Account for uncompacted areas in between areas as pervious surfaces. Solar development is distinct from other types of development in that ability to use ground under the arrays as infiltration areas, if not compacted and appropriately vegetated.
Lot coverage standards do not match disconnection standards.	Lot coverage maximums should generally not be lower than 50 percent and reflect disconnection standards or should exempt arrays where soils are vegetated and uncompacted.
Uncompacted areas in between the arrays can often be classified as impervious surfaces, which is not reflected in field observations and modeling.	Account for uncompacted areas in between areas as pervious surfaces. Solar development is distinct from other types of development in that ability to use ground under the arrays as infiltration areas, if not compacted and appropriately vegetated.
Existing local standards do not recognize disconnection.	Develop model ordinance language for local governments that recognizes disconnection. Include recommendations for lot coverage standards (see above), solar-specific impervious surface definition, and land use recommendations for the use of disconnection as a water quality tool.
Local permitting practices do not consider the importance of disconnection on solar projects.	• Offer training on the scientific foundation for solar-specific standards incorporating disconnection as a BMP or green infrastructure tool. • Offer training on model ordinances that directly address lot coverage and science-based standards for disconnection. • Provide case study examples to help communities become more comfortable with large-scale solar arrays using disconnection as green infrastructure.

Project Best Practices for Water Quality

Array placement in solar development is generally guided by shading considerations (to prevent one array from shading the adjacent array) during preferred production times. Most arrays examined in the study had a spacing of 20 - 25 feet, which appeared to be sufficient disconnection area (with an array design of 1 or 2 panels in portrait orientation) to infiltrate most design storms. For sites with additional challenges (tight soils, greater compaction, steep slopes, etc.), increasing the disconnection between arrays can help mitigate these conditions.

Best Practice	Description
Incorporate disconnection into site design.	Incorporate infiltration areas into array layout and design, particularly for areas with class C or D soils (tight soils, clay) where additional infiltration area may be needed to address some design storms. Recognize that larger panels require both additional separation or disconnection due to more volume at the drip edge (primarily for fixed rather than tracking arrays) and increases the need for dissipation BMPs to ensure sheet flow.
Maximize disconnection opportunities.	• Consider landscape panel orientation (internal array disconnection) to reduce volume at the drip edge, encourage sheet flow, and support vegetation under the array. • Include internal array disconnection in the SWPPP or post-construction plan.
Adopt solar-specific mitigation of runoff under special (more challenging) site conditions.	• Tight soils or high bulk density: efficacy of disconnection as a BMP can be affected by tighter soils (class C or D) or higher bulk density and may require a larger disconnection area or the use of additional BMPs. • Slope orientation relative to array: design array to ensure a parallel layout of the drip edge to contours or install devices to ensure sheet flow from the drip edge. • Forested sites (cleared for solar): greater disconnection or other BMPs may be needed where sites are replacing wooded land covers. Add BMPs to the disconnection to achieve post-construction outcomes equivalent to the forested pre-development standard.

ABOUT THE GREAT PLAINS INSTITUTE

GREAT PLAINS INSTITUTE

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A nonpartisan, nonprofit organization, the Great Plains Institute (GPI) is transforming the energy system to benefit the economy and environment. Working across the US, we combine a unique consensus-building approach, expert knowledge, research and analysis, and local action to find and implement lasting solutions. Our work strengthens communities and provides greater economic opportunity through creation of higher paying jobs, expansion of the nation's industrial base, and greater domestic energy independence while eliminating carbon emissions.

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