RE: Evaluating Options for Relative Land Use Loading Rates from Solar Development Sites

October 11, 2024

TO: Urban Stormwater Workgroup

**Summary of Available Literature:**

There are no known studies evaluating the runoff quality from solar development sites. Several studies have looked at changes in site hydrology, including runoff volume and erosion rates, while others have looked at changes in general soil characteristics. No studies have attempted to differentiate between loads from the pervious surfaces compared to impervious surfaces on the sites, and we are unable to find published studies that have directly evaluated runoff generation on solar farms through field measurement, though some are underway.

Across the studies that are available, there are disagreements about the impacts of solar farm development on hydrologic conditions. There is also recognition that the existing environmental research on solar farms has focused on more ideal sites, potentially missing those that could be more vulnerable to changes in hydrologic processes with solar farm development. Below is a summary of the key takeaways from the available literature and how it might be used to inform relative land use loading rates from solar development sites in CAST.

**Changes to Soil Characteristics**

Through the literature, there is general recognition that soil degradation occurs on solar development sites due to the construction process. During installation of the solar panels, the sites undergo heavy re-grading, loss of vegetative cover, and compaction from heavy equipment. Combined, there is evidence that these activities can hamper carbon sequestration, soil structure, and biological processes when compared to semi-natural soils. Compaction and reduced organic matter has also resulted in reduced water holding capacity of the soils.

One recommendation to account for these changes to soil characteristics is to adjust the hydrologic soil group (HSG) up one letter (from B to C) when assigning curve number values for runoff modeling.

**Changes to Runoff Volume and Erosion Rates**

Impacts on runoff volume have also been evaluated, though exclusively through modeling studies. These studies show runoff volume changes from solar development sites ranging from negligible, to increases of greater than 100%. One promising tool to evaluate changes to runoff volume is the PV-SMART Runoff Calculator from Mulla et al. in Minnesota. The spreadsheet tool allows users to alter variables shown to impact runoff volume (bulk density, soil depth, vegetative cover, panel spacing), and determines the runoff curve number for the site. While model runs across 5 sites in the U.S. found that the NRCS Runoff Curve Numbers overestimated runoff from sites compared to the calculator, that overestimation is largely due to the ability of PV-SMART to account for important site-specific variables like soil depth and vegetative establishment that the NRCS CNs do not consider. That said, model results with and without solar arrays at each of the five experimental sites did show that runoff increased by 14% with arrays present.

It is also acknowledged in the available literature that solar development led to increases in soil erosion rates and total sediment loads from the sites post-development. This is driven largely by increased energy and velocity of water running off the panels.

**Proposed Approach to Relative Land Use Loading Rates**

Based on our spatial mapping capabilities, combined with local data collection challenges, the simplest proposal is to proceed with two land use categories for solar developments in the Phase 7 Model:

1. Solar Impervious – the area of the panels themselves, and the ground underneath them
2. Solar Pervious – the area in the spaces between and around the panels, covered with grass or perennial vegetation.

However, determining relative loading rates from these sites is challenging due to the lack of available literature on nutrient and sediment loads, and the fact that we are unable to parse the impact of the 3-dimensional nature of the panel installations on the loading rates. In other words, the available literature currently addresses runoff volume and erosion potential on the site as a whole, as opposed to discrete loads from the panels, versus the soils beneath the panels. Accounting for the panels as impervious surfaces alone ignores the existence of the pervious surfaces beneath them, which possess the ability to infiltrate some amount of run-on.

Taken together, the changes in soil characteristics at the site suggest that compared to meadow conditions, pasture, or even turf, the pervious areas are likely to produce greater runoff volume, and greater pollutant loading rates, even if by marginal amounts. Below are the proposed approaches:

*Solar Impervious:*

No literature is available to separate out pollutant concentrations from the panels themselves. Given that they are elevated, and there is no feasible way to separate out the loads from under the panels versus the dripline or intermediate spaces, it is proposed that the relative loading rate from the solar impervious acres be similar to that of Buildings and Other. While this category includes potential load sources that are not applicable to solar panels (barren and transitional lands; sediment and detritus on sidewalks; etc.), the potential for erosion due to poor vegetative establishment and high compaction beneath the panels seems enough to offset those factors.

*Solar Pervious:*

Solar Pervious is much more difficult to estimate. Tools such as the [PV-SMART tool] could be used to determine a revised runoff curve number to estimate the difference between runoff at solar development sites under different conditions and make a estimation of the change in loads from these sites. The challenge is that this tool lumps together the impacts from the pervious and impervious portions of the site, as the presence of panels is included in the estimation. Perhaps this is an okay assumption, given that the loads would be adjusted only for the acres between the panels.

To proceed with this option, the USWG would need to establish the parameter conditions for the tool and establish the scenarios to run to come up with a representative Runoff Estimate, that could be scalable. Among those assumptions:

- Soil Type
- Soil Depth
- Bulk Density
- Vegetative Establishment
- Panel Width and Spacing
- Percent Slope

The combination of potential variable can create many different ultimate runoff estimates. The workgroup would have to make a determination about how many scenarios to run, or a set of sufficiently conservative assumptions, until a single value is reached. Once runoff estimate is determined, the USWG would then need to scale that estimate to an estimate of annual runoff, and a pollutant load concentration to determine a relative loading rate.

While this approach may be more precise, it would not necessarily be more accurate than making a best professional judgment determination based on current understanding of soil properties and site characteristics. An alternative option would simply be to select a relative loading rate value that falls somewhere between Turf Grass and Impervious Roads to represent that the degraded soil conditions present higher potential from erosion and runoff, but that infiltration and vegetative establishment at these sites do reduce overall loads compared to impervious surfaces. This estimate could be considered a placeholder until further research is developed to more directly measure pollutant loads and concentrations from solar development sites.

**Annotate Bibliography:**

**Cook, L.M. and R.H. McCuen. (2013). Hydrologic response of solar farms *J. Hydrol*. Eng. 18 536–41. https://doi.org/10.1061/(ASCE)HE.1943-5584.0000530**

A model written in MATLAB was based on the creation of NRCS type II storms for precipitation inputs. A simple water balance for each land surface cell was used to allocate precipitation to storage or loss (runoff). Some modeling results suggest solar panels can increase erosion. The energy and velocity of water draining from the panels is higher, which could cause erosion in soil below the base of the panels, especially if the interspace is bare. Increases (up to 10 times) of kinetic energy were simulated, which could lead to erosion and the need for erosion control measures, but this modeling effort was not validated by field measurements. Field results indicated that the addition of solar panels over a grassy field does not change the volume of runoff, the peak discharge, nor time to peak.

The effect of soil type on the runoff was also examined. The soil group was changed from B soil to C soil by varying the loss rate. As expected, owing to the higher loss rate for the C soil, the depths of runoff increased by approximately 7.5% with the C soil when compared with the volume for B soils. However, the runoff volume for the C soil condition only increased by 0.17% from the pre-paneled condition to the paneled condition. In comparison with the B soil, a difference of 0.35% in volume resulted between the two conditions. Therefore, the soil group influenced the actual volumes and rates, but not the relative effect of the paneled condition when compared to the pre-paneled condition.

**Daniels, L., R. Stewart, J. Ignosh, D. Sample. (2024). Soil-Site Management Protocols & Best Management Practices (BMPs) for Utility Scale Solar Site (USS) Development and Management in Virginia. *White Paper.* https://landrehab.org/home/programs/solar-farms/**

Adjust design BMP SWM volumes to account for (a) site disturbance and (b) panel imperviousness. This effort should include adjusting the Soil Hydrologic Group (HSG) designation per DEQ GM 22-2012 guidance

Unless appropriate remediation measures are taken during site stabilization to alleviate soil compaction and maintain other important soil quality parameters (e.g., aggregation and infiltration), the CN and Rv values utilized for estimating runoff should be higher than for original undisturbed conditions.

Panel imperviousness and its effects on actual runoff versus proper application of runoff modeling parameters is currently controversial and subject to research validation. Conservative adjustment of curve numbers (CN) or other runoff coefficients (e.g., RVs in VRRM) should be included for long term SWM planning.

One recommended approach (also required by DEQ GM 2022-12 as cited earlier) is for users to account for disturbance during the active site development and stabilization phase by adjusting HSG's up one letter (e.g., from B to C) when assigning values for NRCS/TR-55 Curve Numbers

**Lambert, Q., A. Bischoff, S. Cueff, A. Cluchier, R. Gros. (2021). Effects of solar park construction and solar panels on soil quality, microclimate, CO 2 effluxes, and vegetation under a Mediterranean climate. *Land Degradation and Development*, 2021, 32 (18), pp.5190-5202. https://doi.org/10.1002/ldr.4101**

Soil levelling and vegetation removal during solar panel construction may have increased surface runoff and soil erosion. Low C and N content suggest that nutrient cycling was lower solar site soils compared to semi-natural conditions and that several solar farm soil functions (carbon sequestration, soil structure, biological processes) were hampered compared to semi-natural soils. There was also reduced water holding capacity.

The key processes involved in degradation of soil quality were soil tillage and partial topsoil removal increasing erosion (Quinton et al., 2010) and organic matter mineralization. Reduced organic matter content and increase of soil compaction decrease water holding capacity (Mujdeci et al., 2017) and soil stability (Simansky et al., 2013).

**Liu, H., Wu, C., Yu, Y., Zhao, W., Liu, J., Yu, H., et al. (2023). Effect of solar farms on soil erosion in hilly environments: A modeling study from the perspective of hydrological connectivity. Water Resources Research, 59, e2023WR035067. https://doi. org/10.1029/2023WR035067**

Results show that the Utility-Scale Solar Farms (USF) considerably increased runoff (99.18%–154.26%) during its operational period. USF also increased soil erosion rate

(21.4%–74.84% and 25.35%–76.18%) and Hydrologic Conductivity (HC) (0.08%–0.26% and 0.47%–0.91%) throughout construction and operational periods, respectively. The highest erosion rates were detected in the installation zones and in the areas close to the river channel. The study concluded that there is support for the hypothesis that hydrologic conductivity (HC) is a critical indicator for sediment yield in a USF, and thus the long-term responses of soil erosion to USF installation and development can be explained in terms of HC.

**Luis Mier-Valderrama, Julianna Leal, Humberto L. Perotto-Baldivieso, Brent Hedquist, Hector M. Menendez, Ambrose Anoruo, Benjamin L. Turner. (2024) Evaluating soil erosion and runoff dynamics in a humid subtropic, low stream order, southern plains watershed from cultivation and solar farm development. International Soil and Water Conservation Research, Volume 12, Issue 2, 2024, Pages 432-445, ISSN 2095-6339, https://doi.org/10.1016/j.iswcr.2023.09.004.**

Experiments were conducted by varying precipitation depth, duration, and land uses: native vegetation pre-cultivation (control), cultivation (current), current conditions with 15% solar farm conversion (solar), and current conditions with 30% solar farm conversion (solar x2). Shifting to solar farming led to significant increases in cumulative sediment load (+12%–30%), with no significant differences in peak discharge rate changes (+0.38%–4%).

**Mulla, D., Galzki, J., Hanson, A., & Simunek, J. (2024). Measuring and modeling soil moisture and runoff at solar farms using a disconnected impervious surface approach. Vadose Zone Journal, e20335.** https://doi.org/10.1002/vzj2.20335

Predicted runoff depths were strongly affected by precipitation depth, soil texture, soil profile depth, and soil bulk density. Runoff depths across the five experimental sites averaged 13%, 25%, and 45% of the 2-, 10-, and 100-year design storm depths, clearly showing that these solar farms do not behave like impervious surfaces, but rather as disconnected impervious surfaces with substantial infiltration of runoff in the vegetated areas between and beneath solar arrays.

Model results with and without solar arrays at each of the five experimental sites showed that runoff increased by 14% with arrays present. While a similar result was obtained by Nair et al. (2023) for solar arrays installed on a site with a 23% slope, Gullotta et al. (2023) stated that there were no differences in runoff between sites with or without solar arrays

**Yavari, R., D. Zaliwciw, R. Cibin, and L. McPhillips. (2022). Minimizing environmental impacts of solar farms: a review of current science on landscape hydrology and**

**guidance on stormwater management. *Environ. Res.: Infrastruct. Sustain*. 2 032002. [https://doi.org/10.1088/2634-4505/ac76dd](https://doi.org/10.1088/2634-4505/ac76dd)**

Research on a solar farm in Colorado, USA observed a greater coarse particle fraction on the solar farm as compared to an adjacent native grassland reference. The reason for the difference in particle size is likely the soil disturbance and vegetation removal during the construction phase of the solar farm, which causes erosion of the fine particles (Choi et al 2020a).

At a solar farms on reclaimed cropland with meadowgrasses, there were no significant differences in soil physical and chemical properties, as compared to a reference site (Armstrong et al 2016).

Unsaturated hydraulic conductivity was found to be higher beneath solar panels on a solar farm in Colorado than at the edge or interspace area between panels (see the schematic of example solar farm in figure 1). The reason for this difference may be the reduced exposure to maintenance activities beneath the panel, which could induce compaction.

At the time of the writing of this review, the evaluation of runoff generation has occurred only in published modeling-based studies. From this work, regardless of the orientation and tilt angles, runoff volume increases after solar panel installation. Impacts on peak flow are more variable, with the orientation of panels either increasing or decreasing peak flowrates. The results indicate that the panels also noticeably change the rain distribution onto the land surface.

Construction of solar farms can require substantial land manipulation. Thus, it is also important to consider this in erosion estimates, and manage this impact appropriately.

At the time of this review, the authors were unable to find any study that directly evaluated runoff generation on solar farms through field measurement. Thus, we are still lacking critical insight into whether solar farms change runoff generation, and whether existing site and stormwater management practices are adequate to prevent adverse impacts. As a result, existing hydrologic models of solar farms are largely uncalibrated. There is also a bias in the sort of sites being evaluated. In general, existing environmental research on solar farms has focused on more ideal sites, i.e. those on sites with lower slopes and well-draining soils. Thus, we are neglecting sites that could be more vulnerable to changes in hydrologic processes with solar farm development.

**Other References Reviewed:**

Great Plains Institute. 2021. Photovoltaic Stormwater Management Research and Testing (PV-SMaRT) Potential Stormwater Barriers and Opportunities. https://betterenergy.org/wp-content/uploads/2021/10/PV-SMaRT-Potential-Stormwater-Barriers-and-Opportunities.pdf.

McPhillips, L., A. Buda, Z. Easton, W. L. Daniels, S. Fathel, J. Ignosh, C. Raj, D. Sample. 2024. Best Management Practices to Minimize Impacts of Solar Farms on Landscape Hydrology and Water Quality. STAC Publication Number 24-001, Edgewater, MD. 42 pp.

McPhillips, L., R. Yavari, & C. Raj. 2024. Understanding and managing impacts of solar farms on landscape hydrology: insights from field monitoring and modeling. Presentation to the Choose Clean Water Workgroup. Annapolis, MD. September 4, 2024.