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TOPICAL REVIEW

Minimizing environmental impacts of solar farms: a review of current science on landscape hydrology and guidance on stormwater management

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Abstract

As solar energy becomes an increasingly cheap source of renewable energy, major utility-scale ground solar panel installations, often called 'solar farms', are rapidly growing. With these solar farms often covering hundreds of acres, there is the potential for impacts on natural hydrologic processes, including runoff generation and erosion. Here we review the current state of scientific research on the hydrology and water quality impacts of solar farms, as well as management recommendations for minimizing any impacts. The limited field measurements indicate the redistribution of soil moisture around solar farms, but the net impacts on runoff and erosion are less clear. Research focused on coupling solar farms with agriculture as 'agrivoltaics' demonstrates reduced evaporative water losses and associated crop stress, particularly in more arid regions. With regards to land and the stormwater management associated with solar farms, most US states currently do not have solar farm-specific recommendations and instead defer to standard stormwater management permits and guidance. In states with solar farm-specific guidance, typical recommendations include minimizing construction-related compaction, ensuring a high cover of perennial vegetation with minimal maintenance, and designing with pervious space between solar panel rows to promote infiltration of any runoff; in some cases, structural stormwater management like infiltration basins may be required. In general, solar farms can be designed to minimize the impact on landscape ecohydrological processes, but more research is needed to determine whether current recommendations are adequate. In particular, there is a need for more field research on less ideal sites such as those with higher slopes.

1. Introduction

The advancement of human civilization depends on energy. Societies are growing, and the standard of living is rising, resulting in a growing demand for energy. The use of fossil fuels as a major energy source has led to environmental pollution and global warming. In addition, fossil fuels are not renewable. In recent decades, there has been a search for cheaper, affordable and more environmentally friendly and sustainable energy sources (Gunerhan *et al* 2008, Shorabeh *et al* 2019).

Amongst sustainable energy sources, solar energy is favored, owing to its plenitude and increasing affordability. It is more abundantly distributed in nature than any other renewable energy source. Solar energy has widely and exponentially grown in the last couple of decades (US Energy Information Administration (EIA) 2020). Solar photovoltaic (PV) technology converts the Sun's energy to environment-friendly electricity (Solangi *et al* 2011). This has been one of the most booming forms of renewable energy in recent years, due to technological advancements and favorable government policies that have made it increasingly affordable and accessible (Gunerhan *et al* 2008, Hassanpour Adeh *et al* 2018, Shorabeh *et al* 2019). PV development can also be beneficial in terms of potentially supporting the reclamation of degraded land, economic opportunities, and rural electricity access. (Ravi *et al* 2016). It also avoids the greenhouse gas impacts, air quality concerns, and other sources of pollution caused by fossil fuels (Aman *et al* 2015, Hernandez *et al* 2014, Grigorescu *et al* 2019, Lambert *et al* 2021, Shorabeh *et al* 2019, Taha 2013, Vrînceanu *et al* 2019).

PV technology is deployed in various ways. One popular approach leverages the rooftops of residential or commercial buildings for solar panel installation, where solar panels are impervious panels of PV cells. Solar panel arrays mounted on the ground are another way of harvesting solar energy, particularly at a larger scale compared to residential rooftop solar. Utility-scale ground solar panel installations used for electricity generation of 1 MW or greater are commonly referred to as 'solar farms' (US Energy Information Administration (EIA) 2020). On solar farms, solar panels are mounted on metal supports, with panels arranged in long rows. The area under and between the panels could be paved, covered with gravel, bare soil, or vegetated. The interspace between the rows, as well as access paths or roads between clusters of rows, allows for maintenance as well as possible infiltration of water (Barnard *et al* 2017a, Gunerhan *et al* 2008, Zhu *et al* 2019).

Utility-scale solar energy development needs a lot of space, and its large-scale installation could potentially have some negative impacts on the environment, but this depends on the way that the solar farm is built and maintained (Hernandez *et al* 2019, 2014, Moore-O'Leary *et al* 2017). The area covered by solar farms can vary between 1 acre (0.40 ha) to several hundred acres, depending on the power generation capacity. The construction process of solar farms can require extensive landscape modification that could result in the modification of soil properties and vegetation (Aman *et al* 2015, Jacobson and Delucchi 2011). The addition of an impervious surface, as solar panels, could alter the site's hydrology and impact erosion. Changes in vegetation and ongoing maintenance of the site can also impact soil carbon dynamics and habitat provision (Barnard *et al* 2017a, Choi *et al* 2020a, Gunerhan *et al* 2008, Moore-O'Leary *et al* 2017, Walston *et al* 2021). There is increasing interest in leveraging solar farms for the provision of additional ecosystem services or benefits beyond solar power generation. This could include planting of certain vegetation to create pollinator habitats (Blaydes *et al* 2021, Graham *et al* 2021, Walston *et al* 2021, 2018). The concept of 'agrivoltaics' involves leveraging the solar farm for agriculture, such as sheep grazing or crop cultivation (Weselek *et al* 2019).

As solar energy becomes an increasingly cheap source of renewable energy, the number of solar farms is rapidly growing. As of 2022, there are approximately 5500 major solar projects across the US, with existing installations generating 55 GW, and projects under construction or in development generating 110 GW (Solar Energy Industries Association 2020). Thus, it is critical to ensure that these projects are implemented in the most sustainable way.

There is a small but growing body of scientific research seeking to understand the impacts of solar farms, specifically on landscape ecohydrology in a range of environmental and land conditions. Similarly, there are rapidly evolving guidance and/or regulations on best land development practices related to solar farm implementation. Thus, we seek to synthesize the current state of scientific knowledge and management recommendations, as well as to identify gaps. We review the current science on how solar farms impact landscape hydrology and related soil and vegetation characteristics, as well as review the current state of land and stormwater management guidance in US states with respect to solar farms.

2. Methods

In order to review the current science on solar farm hydrology, in mid-2022 we sought relevant scientific literature using Google Scholar and Web of Science to perform searches with the following key words: (solar farm, PV, or agrivoltaic) and (hydrology, stormwater management, soil moisture, runoff, or evapotranspiration). We have also followed references cited in these articles to identify additional relevant articles. This yielded 18 usable articles which are reviewed.

In addition, we reviewed available information on land and stormwater management recommendations from US states. In the US, most states have authority delegated from the US Environmental Protection Agency to oversee permitting processes related to land development under the National Pollutant Discharge Elimination System (NPDES). States may also choose to enact their own regulations relating to solar farm development and/or stormwater management. We searched the websites of US state agencies with jurisdiction over stormwater management regulations, in order to summarize the available rules and guidelines specific to stormwater management on solar farms. If we could not find stormwater management information specific to solar farms for a given state, we also attempted to contact the agency directly for information.

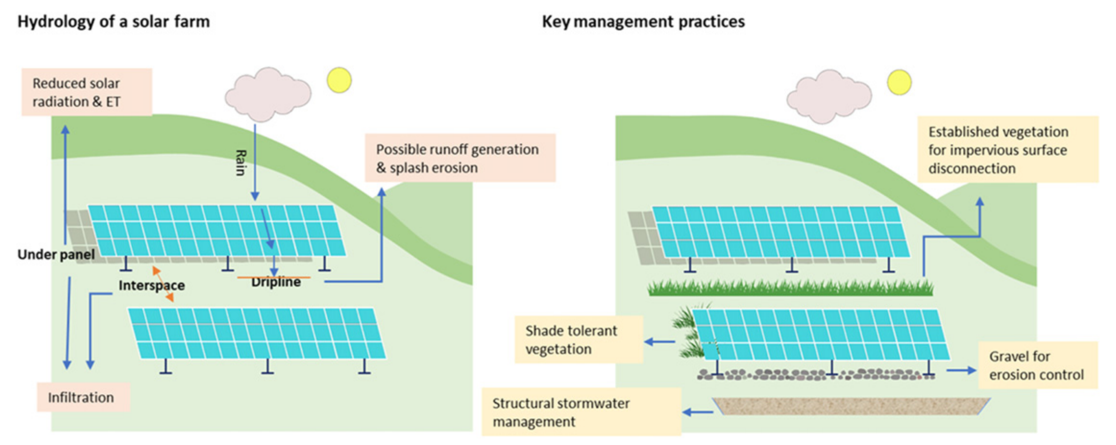

Figure 1. Key hydrological phenomena on a solar farm (left) and some example management practices for addressing stormwater management (right).

3. Review of scientific research on solar farm hydrology

Research on the landscape hydrology of solar farms is comprised of field-based and computational modeling studies. Field-based studies primarily address hydrologic components and landscape biophysical attributes, including soil moisture patterns, evapotranspiration, soil properties, and vegetation characteristics (table 1). Field studies span multiple continents and climatic zones, including Asia, North America and Europe. Modeling studies focus on simulating soil moisture, runoff generation, and erosion (table 2).

3.1. Solar farms and soil properties

Given that solar farms involve major construction activities during the site development process, there is potential for them to have impacts on soil properties and vegetation. Soil physical and chemical properties directly impact hydrologic processes, and thus we begin our review with understanding these impacts.

Some physical, chemical, and biological soil indicators can be lower on solar farms compared to semi-natural land cover types, depending on solar farm management strategies. Research on a solar farm in southern France with silty clay soils did not find differences in soil bulk density on solar farms as compared to semi-natural pinelands and shrublands, but did find a reduced water holding capacity (Lambert *et al* 2021). 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).

Some studies have found the carbon and nitrogen content to be lower in the soil on solar farms than in reference soils (Choi *et al* 2020a, Lambert *et al* 2021). Basal respiration and microbial biomass have also been measured at lower quantities on solar farms compared to reference land covers (Lambert *et al* 2021). However, at a solar farm on reclaimed cropland with meadow grasses, there were no significant differences in soil physical and chemical properties, as compared to a reference site (Armstrong *et al* 2016). There were some differences in soil biological indicators such as respiration, but the differences were not consistent throughout the year.

Some soil properties may also vary within the solar farm. 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 and reduce hydraulic conductivity (Choi *et al* 2020a). This in turn can impact patterns of soil moisture distribution, which is discussed later in section 3.4.

3.2. Solar farms, micrometeorology, and evapotranspiration

The presence of solar panels has the potential to alter multiple meteorological properties. They may change the balance of incoming solar radiation and emitted radiation, in turn altering soil temperature and evapotranspiration. The fact that they are typically mounted some distance above the ground and inclined may also affect wind dynamics. Additionally, the type and health of vegetation affects actual evapotranspiration (AET) rates, where vegetation may be influenced by the solar panels as well as by human management decisions.

Reduced solar radiation from shading has been documented beneath solar panels on solar farms in France, the United Kingdom, and Oregon and Nevada, USA. This results in lower mean daily soil and air temperatures

Table 1. Summary of the reviewed field-based studies on solar farm hydrologic phenomena, highlighting the basic study location and types of measurements made on hydrologic and related variables. An ‘x’ indicates that measurements were made for variables in the given category.

Source	Site characteristics			Types of measurements				
	Location	Climate zone	Solar farm info	Micro-meteorology	Soil Phys/Chem/ Bio properties	Veg-etation	Soil moisture	Runoff
AL-agele *et al* 2021	Corvallis, Oregon USA	Mediterranean warm, cool summer climates	0.8 ha agrivoltaic vegetable farm with 18 degree panel tilt. Silty clay loam soil	x	—	x	x	—
Armstrong *et al* 2016	Swindon, United Kingdom	Oceanic climate	Land cover prior to construction: the field site was arable cropland and was sown with a species-rich After construction: the control and interspace of the solar farm were re-seeded with species-rich meadow mixture meadow mixture	x	x	x		
Barron-Gafford *et al* 2019	Tucson, Arizona, USA	Arid climate, hot desert	Agrivoltaic site with crops (tomatoes, jalapenos, and chiltepin plants). Native soil was replaced with an organic garden blend (organic compost and an organic garden blend (organic compost and sandy soil) Age of the solar site: less than one year	x	—	x	x	—
Choi *et al* 2020a	Northern Jefferson County, Colorado, USA	Cold semi arid	The treatment site is revegetated with native grasses similar to the undisturbed condition (control point) Surficial soils at the solar site are paleosols with clay-enriched subsoil Age of the solar site: 8 years	x	x	—	x	—
Elamri *et al* 2018a, 2018b	Montpellier, France	Mediterranean hot summer	Agrivoltaic system (lettuce) with varying panel density and tilt. oil type is loamy clay deep alluvial soil (same site as Marrou et al. with updated ability for variable panel tilt)	x	—	—	x	—
Hassanpour Adeh *et al* 2018	Corvallis, Oregon USA	Mediterranean warm, Oregon USA	Agrivoltaic site with pasture. The soil classification for both the control and agrivoltaic systems is Woodburn silt clay Age of the solar site: 2 years	x	—	x	x	—
Lambert *et al* 2021	Southern France	Mediterranean hot summer climates	Soil type of solar farms are carbonatic pedofeatures Different control points with a land cover of pinewood, shrubland and abandoned vineyards were selected	—	x	x	x	—

(*continued on next page*)

Table 1. Continued Summary of the reviewed field-based studies on solar farm hydrologic phenomena, highlighting the basic study location and types of measurements made on hydrologic and related variables. An 'x' indicates that measurements were made for variables in the given category.

Source	Site characteristics			Types of measurements				
	Location	Climate zone	Solar farm info	Micro-meteorology	Soil Phys/Chem/ Bio properties	Veg-etation	Soil moisture	Runoff
Marrou 2013b *et al* 2013a,	Montpellier, France	Mediterranean hot summer climates	Agrivoltaic system (lettuce and cucumber) with varying panel density and a fixed 25 degree tilt. The soil type is loamy clay deep alluvial soil (same site as Elamri *et al* 2018a)	x	—	x	x	—
Uldrijan *et al* 2021	South Moravian Region, Czech Republic	Oceanic climate	The soil has textures of loamy-sand to clay-loam, vegetated with perennial grass mixture Age of the solar site: 7 years	—	—	x	—	—
Wu *et al* 2022	Northwestern China	Arid climate, cold desert	Solar farm with a panel tilt of 37.5 degrees, where a panel row is comprised of two adjoining sub panels with a 3 cm gap. Mixed gravel and sand soil substrate	—	—	—	x	—
Yue *et al* 2021	Western China	Arid climate, cold desert	The soil material is loess or gravel, soil texture is mainly sandy loam and light silt loam The main plant species are shallow-rooted plants Some of panels are fixed and some are rotating	x	—	—	x	—

Table 2. Summary of reviewed studies performing hydrological modeling of solar farms.

Source	Solar farm info	Modeling approach	Target variable(s)
Barnard *et al* 2017a	Three solar farm sites in west Texas and one solar site in Georgia USA (humid subtropical climate)	Flo-2D/HEC-HMS maps of maximum flow depth and velocity	The final products are
Cook and McCuen 2013	No specific geographic location Different scenarios: • Slope 1%–5% • Soil type B and C • Panel angle 30, 45 and 70 • Vegetation type: bare ground	Custom model in MATLAB (Water balance, Manning's Eqn)	Runoff depth, peak flow, erosion potential
Edalat 2017	Two solar farms in Nevada USA (arid climate) • Urban • Outside urban area	HEC-HMS	Runoff depth/peak flow
Elamri *et al* 2018b	Agrivoltaic solar farm in Montpellier, France (mediterranean hot summer	Hydrus 2D with custom AVrain module to simulate rain redistribution of panels	Solar panel rain redistribution /runoff, soil moisture
Pisinaras *et al* 2014	Low, medium, and high intensity solar the farm scenarios for sub-basins in 1%–5% of Vosvozis River watershed in northern Greece (Mediterranean hot summer climate) Solar farm scenarios replaced existing agricultural land use	SWAT	Surface runoff, infiltration, evapotranspiration
Walston *et al* 2021	Midwest United States (hot summer, continental climate) land use scenarios: • Agriculture scenario • Solar-turfgrass scenario • Solar-native grassland scenario	InVEST ecosystem services model	Sediment retention, water retention
Wu *et al* 2022	Solar farm in northwestern China (arid, cold desert climate)	Custom model using energy balance, AVrain and single bucket water balance	Soil moisture and temperature

below the panels in comparison to full sun reference sites during the spring and summer (AL-agele *et al* 2021, Armstrong *et al* 2016, Hassanpour Adeh *et al* 2018, Marrou *et al* 2013b, Yue *et al* 2021). Remote sensing of land surface temperature at a solar farm has also indicated overall reductions in soil temperature across the site as compared to pre-development data, though this approach could not explicitly evaluate changes below the panels (Edalat 2017). Wind and humidity changes were not as consistent. Wind speed and vapor pressure deficit did not change relative to solar panels at a solar farm in France (Marrou *et al* 2013b). However, wind speed, direction, and relative humidity were all altered around solar panels, as compared to the reference site at a solar farm in Oregon (Hassanpour Adeh *et al* 2018), and vapor pressure deficit decreased under solar panels on solar farms located in the United Kingdom and Arizona USA (Armstrong *et al* 2016, Barron-Gafford *et al* 2019).

There can be temporal variability in how solar farms affect meteorological properties and resulting soil dynamics. For example, solar panels decreased the soil temperature beneath the panels compared to reference sites, but these differences were more substantial in spring versus summer (Lambert *et al* 2021). Increases in soil temperature beneath solar panels relative to reference sites have also been observed during autumn and winter periods at solar farms located in the United Kingdom and western China, when solar panels may help prevent loss of longwave radiation (Armstrong *et al* 2016, Yue *et al* 2021). Remote sensing observations of the land surface temperature in Nevada found temperature differences to be greatest in winter when the Sun was lower and the shadows from solar panels were larger (Edalat 2017).

Reductions in solar radiation generally translate into reduced potential evapotranspiration (PET) under solar panels (Elamri *et al* 2018a, Hassanpour Adeh *et al* 2018). Solar farm impacts on evapotranspiration dynamics have been investigated in depth on prototypes of agrivoltaic systems in France, testing two crops (cucumber and lettuce) and two solar panel configurations (full panel density vs half density (Marrou *et al* 2013a). Results show that PET and AET were higher in the full Sun reference locations compared to the solar farm agrivoltaic sites. The reduction in AET was slightly more at the full density solar farm as opposed to the half density site, and differences also varied by crop type. For the lettuce agrivoltaics site, AET over the measured growing period was 103 mm at the full Sun reference, but reduced to 81 and 79 mm for the half density and full density solar farm sites, respectively. Similarly, at the cucumber agrivoltaics site, AET was 178 mm at the full Sun reference, but reduced to 153 and 145 mm at the half density and full density solar farm sites, respectively. In general, ET fluxes were more affected in spring than in summer, indicating temporal variability in the solar panel influence (Marrou *et al* 2013a). The ratio of transpiration to evaporation also changed, increasing 3 – 4 times in the shaded area of the solar farm sites.

Additional research at this same agrivoltaic site explored the impact of variable panel tilting/tracking on solar radiation and ET (Elamri *et al* 2018a). While there was still a net reduction in solar radiation and ET under panels with panel tracking, it led to much less heterogeneity than at the sites with a fixed panel orientation.

3.3. Solar farms and vegetation

As with soil properties, vegetation on solar farms is a function of both initial human management decisions regarding the initial solar farm development, and ongoing operations and maintenance decisions on the solar farm. It is also affected by interactions with site soil properties and hydrology. Vegetation is explicitly leveraged as a stormwater management practice, as described later in this review, and is a critical managed element of agrivoltaics operations where solar farms are leveraged for the additional co-benefits of crop production. Thus we feel it is important to review what is known about changes in vegetation on solar farms.

Existing field research has focused on the assessment of vegetation coverage, biomass, and diversity, as well as on interactions with hydrologic processes via water use efficiency or water productivity. Findings are quite variable in these limited studies. Surveys of a solar farm (non-agrivoltaic site) in France largely found no major differences in plant community composition and coverage, relative to nearby reference shrubland and pineland sites. There was a slight increase in the relative abundance of shadow-tolerant plant types under solar panels (Lambert *et al* 2021). At a reclaimed brownfield site in the Czech Republic, where the land was sown with a meadow grass mixture during solar farm development, differences in plant composition within the solar farm were observed in a survey eight years after the initial development (Uldrijan *et al* 2021). A greater abundance of taller native perennial grasses was documented in the interspace between panel rows, where more shade-tolerant species and sometimes invasive grasses were observed beneath panels. At a solar farm in the United Kingdom, reduced plant species diversity was observed under solar panels, with reference and panel interspace areas dominated by forbs and legumes (Armstrong *et al* 2016).

Both increases and decreases in vegetation biomass have been documented under solar panels, depending on the climatic zone. In the areas with lower solar radiation (solar farms in the United Kingdom and the Czech Republic), reduced vegetation coverage and reduced biomass (up to four times lower) have been documented beneath solar panels, relative to panel interspace or reference areas (Armstrong *et al* 2016, Uldrijan *et al* 2021). However, the results of research in the solar farm located in Oregon show 126% more dry biomass beneath solar panels relative to the interspace zone and 90% more dry biomass relative to the reference site (Hassanpour Adeh *et al* 2018). This site is less energy-limited. Thus, the shading of solar panels helps to reduce ET losses and in turn to maximize the water use efficiency of plants, as well as to increase biomass. At crop agrivoltaic sites in Oregon and France, some reduction in crop yield and biomass has been observed under panels relative to nearby reference sites (AL-agele *et al* 2021, Elamri *et al* 2018a). At sites with solar panel tracking, biomass was only 16% less than the reference, compared to 30% or greater reductions at fixed panel sites (Elamri *et al* 2018a).

More efficient water use has been observed under solar panels in multiple cases, mainly because of the shading and reduced solar radiation and PET under the panels. This is particularly evident in locations abundant in solar radiation. In an agrivoltaics solar farm in Arizona, USA, the shade of the solar panels reduced plant drought stress and led to greater crop and food production (Barron-Gafford *et al* 2019). More efficient water use was also observed for lettuce crops in an agrivoltaics solar farm in France. Coverage of soil by crops was found to be important in reducing soil evaporation and maximizing the availability of water for transpiration and biomass production (Marrou *et al* 2013a). Water productivity also improved in the shade of panels at a tomato agrivoltaic site located in Oregon (AL-agele *et al* 2021). Modeling of water and vegetation dynamics at agrivoltaic sites in France successfully reproduced field data on rain and soil water redistribution, and allowed for the additional scenario exploration of plant-water interactions and optimization. The modeled scenarios indicated that the tilting of solar panels could help to minimize water interception and the associated redistribution of water. The scenarios also indicated that agrivoltaics could improve water productivity relative to more traditional agriculture, with only small reductions in crop yield (Elamri *et al* 2018a, 2018b).

3.4. Impact of solar panels on soil moisture distribution

On solar farms, the impervious surface of solar panels intercepts precipitation and drains the water into the interspace between panels. Previously discussed changes in evapotranspiration and soil physical and chemical properties can interact with this altered surface hydrology to cause some heterogeneity in the soil moisture content on solar farms.

Field measurements of the soil moisture on solar farms have often been focused on key locations relative to the solar panels. These have included the interspace area fully open to the sun between panels, under the lower front edge of the panel or 'dripline', underneath the center of the panels, and at the back (higher) edge of the panels where there is partial Sun (figure 1). Sometimes measurements may also be made at a control or reference area outside the main array of panels. At a solar farm in western Oregon, USA on silt clay soils, the soil beneath the center of solar panels was consistently wettest, followed by soil under the back edge of solar panels, and nearby reference soils, with the interspace soils being driest. At a 0.6 m depth, soil under the center of the panels remained near saturation (∼30% volumetric water content (VWC)), whereas the interspace area depleted from ∼30% to ∼20% VWC by the end of the growing season (Hassanpour Adeh *et al* 2018). Similar patterns have been observed at solar farms in China (Wu *et al* 2022, Yue *et al* 2021). Soil moisture at a northwest China site was wettest (10%–20% VWC) at the main dripline at the front of panels as well as under the center of the panel row where a small gap in panels was located; soils at the back edge of panels and nearby reference soils were driest (5%–10% VWC; Wu *et al* 2022). At an arid western China solar farm, soil moisture was consistently higher under panels—14.7% higher under fixed tilt panels compared to 11% higher under variable tilt panels (Yue *et al* 2021). Soil moisture was also consistently higher under solar panels at an agrivoltaics site located at Arizona, USA, as compared to an agricultural control site (Barron-Gafford *et al* 2019). At a solar farm in Colorado, USA (cold semi-arid climate) with paleosols and clay subsoil, some soil moisture variability was observed. Dripline soils were consistently higher (up to 20% – 30% VWC), especially following rain events (Choi *et al* 2020a). However, substantial variability in soil moisture at all locations relative to solar panels led to a lack of statistically significant differences. The reference site at nearby native grassland was consistently lower in moisture (∼5%). At an agrivoltaic site in France, higher soil moisture was observed at panel driplines, while soil moisture was lower under the panels and in the interspace (Elamri *et al* 2018b). Another solar farm in France did not demonstrate differences in soil moisture under solar panels compared to the interspace, but did observe overall reduced soil moisture at the solar farm sites as compared to a shrubland reference (Lambert *et al* 2021). Overall, the main panel dripline at the front of solar panel rows is consistently wetter, and interspace zones tend to be drier. However, under panel soil moisture may vary depending on the balance of evapotranspiration and runoff contributions, due to the climate and panel design.

There have also been some efforts to model soil moisture dynamics on solar farms. These studies have created or leveraged models of rain redistribution from solar panels, and then combined this with various approaches of water and energy balance representation to simulate soil moisture (Elamri *et al* 2018b, Wu *et al* 2022). In both cases, there was reasonable agreement between observed and simulated soil moisture. Suspected causes of inaccuracy included challenges in representing the complex energy dynamics under solar panels that influence evapotranspiration (Wu *et al* 2022) as well as challenges in the accurate representation of water redistribution (Elamri *et al* 2018b).

3.5. Solar farms and runoff

To our knowledge, at the time of the writing of this review, the evaluation of runoff generation has occurred only in published modeling-based studies. Many of these studies leverage existing modeling programs, with certain modifications used to represent the unique land cover type of the solar panels. None of these published studies, to our knowledge, have validated their models with field data specific to solar farms.

HEC-HMS (US Army Corps of Engineers 2021) has been leveraged in multiple studies. In one study, the runoff on a solar farm was simulated using a linked model which used a combination of Flo-2D and HEC-HMS (which uses a one-dimensional approach). To simulate the flow from upgradient catchments to the solar farm catchment, HEC-HMS was used. USDA Natural Resource Conservation Service Curve Number methods and shallow water equations were used to predict and route stormwater runoff across FLO-2D grids. The results were reported as maps of maximum flow depths and velocities (Barnard *et al* 2017a). HEC-HMS has also been used to study hydrologic dynamics in a Nevada, USA (arid climate) solar farm (Edalat 2017). It is shown that 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 flow rates. The results indicate that the panels also noticeably change the rain distribution onto the land surface. Therefore, panel orientation and tilt angles are important factors that need to be considered in stormwater channel design to carry runoff peak flow. One major limitation of this study was that solar panels were represented as an impervious surface on the ground, and infiltration could not be permitted under the panels, as would occur at an actual site; thus this approach likely overestimates runoff (Edalat 2017).

SWAT has also been leveraged for assessing the impact of solar farms on watershed hydrology (Pisinaras *et al* 2014). For a watershed in northern Greece, scenarios were implemented that induced land use change from agriculture to solar farms in 1 or 5% of the watershed area. Solar farm implementation was represented using soil physical property changes, curve number increase associated with imperviousness, ground cover change from cultivated to bare soil, and reduced solar radiation. The model demonstrated increased surface runoff and percolation, and decreased ET due to solar panel implementation, but these changes were not significant at the watershed scale. However, there is the potential for local-scale impacts. For example, there were increases of ∼100 mm in surface runoff for a given sub-basin, even for a low impact scenario of solar farm implementation (Pisinaras *et al* 2014).

Other research has relied on custom-built models for representing solar farms (Cook and McCuen 2013). A model written in MATLAB was based on the creation of NRCS type II storms for precipitation (hyetograph) inputs. A simple water balance for each land surface cell was used to allocate precipitation to storage or loss (runoff). Manning's equation was used to estimate runoff velocity and the associated kinetic energy relating to splash erosion. Model scenarios were constructed for a 30 cell grid solar farm, where each cell could have a portion allocated as wet, dry, or interspace. A variety of characteristics were manipulated to simulate changes in soil types, solar panel spacing, vegetation roughness, etc. The 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. In general, it was not anticipated that structural stormwater management would be required to prevent adverse impacts (Cook and McCuen 2013).

Some US states, such as Minnesota, have recommended a simple modification to the calculation of impervious surface used in typical runoff modeling approaches for stormwater management planning. Minnesota's recommendation for the modification of runoff calculations leverages the ratio of impervious to pervious surface, where the pervious surface considers both the interspace area as well as the area directly below the panels. Runoff depth associated with this impervious to pervious ratio, as well as soil type, is determined using an Excel tool that leverages the output of an extensive series of models generated in XP-SWMM (Minnesota Pollution Control Agency 2019).

3.6. Solar farms and erosion

Research on the impacts of solar farms on erosion is quite limited. 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 (Cook and McCuen and 2013).

A larger-scale modeling assessment has quantified changes in erosion and associated sediment loss, along with multiple other ecosystem services for hypothetical solar farms in the Midwestern US. These solar farm scenarios focused on vegetation, comparing hypothetical solar farms with native grassland or turfgrass with baseline agricultural land use. Modeling with InVEST, which leverages the revised universal soil loss equation, estimated sediment export under the solar-native grassland scenario to be 0.007 tons/ha/year, which was a reduction of over 95% and 77% compared to the agriculture and solar-turfgrass scenarios, respectively (Walston *et al* 2021). However, erosion estimates were based largely on landscape characteristics such as vegetated cover or slope and did not explicitly represent the fact that solar panels are elevated off the ground.

This existing work largely focuses on the potential for erosion on solar farms after initial construction. However, 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 (see discussion in section 4). In addition to erosion associated with runoff, aeolian erosion is a concern in more arid environments, particularly when presence of vegetation is limited (Ravi *et al* 2016).

4. Review of guidance from US states on solar farm development and stormwater management

In our review of the guidelines and rules of different US states regarding stormwater management on solar farms, a major finding was that most states (close to 30) do not have any guidance for stormwater management specific to solar farms. For ten states, no definitive information was found online and no answer was received to email inquiries, and it is assumed that there is no solar farm specific guidance. In general, these states without specific guidelines defer to their standard rules regarding construction and stormwater management. This typically means that for construction that disturbs a certain area of land (often specified as 1 acre), the solar farm developer would need to follow requirements under the construction general permit for stormwater management. There also may be post-construction stormwater management requirements. The management of construction-related stormwater impacts is required to be managed by states or the US Environmental Protection Agency (US EPA) under the EPA's National Pollution Discharge Elimination System (NPDES) (US EPA 2015).

Twelve US states currently have solar farm-specific guidance relating to managing stormwater (table 3). These states are largely located in the north-central, eastern, and northwestern US. Guidelines from these states rely heavily on 'low impact development' practices (Davis 2005). This involves minimizing initial impacts on the site during the construction process, as well as strategically planned development and site operations that maintain the natural characteristics of the land to mitigate stormwater. The stormwater management functions desired involve runoff volume reduction via infiltration and, to a lesser degree, evapotranspiration; these processes are in turn dependent on soil properties and vegetation. The reduction of erosion and/or retention of sediment relies on reducing the velocity of runoff through infiltration and enhanced surface roughness, particularly from vegetation (Davis *et al* 2012).

Some guidance relates to the initial site selection process for the solar farm. It is recommended to avoid soils with a slip potential, and well-draining soil types are ideal. Lesser sloped sites are ideal, though there is substantial variability in the recommended slope thresholds (e.g. Maryland recommends 5% or less, while other states recommend less than 10%). With considerations such as the slope or soil hydrologic class, certain categories (e.g. poorly draining soils or higher slopes) are generally permissible for solar farms, but would require additional structural stormwater management to be added (discussed further below).

During the construction process, it is recommended that soil compaction and disturbance be minimized, in order to maintain the soil's natural ability to infiltrate runoff. It is also critical to implement temporary erosion and sediment controls to prevent any impacts during the construction process. This may include erosion control socks, temporary sedimentation basins, or mulching the bare soil surface.

Another group of recommendations relates to how the solar farm site is designed. A key stormwater management practice mentioned by most states with specific guidance is to maintain a certain interspace distance between rows of solar panels. This leverages the 'low impact development' principle of disconnecting impervious surfaces. The pervious interspace between solar panel rows serves to promote infiltration of any runoff and the retention of eroded sediment. In this interspace, as well as under the panels, it is often recommended to maintain a certain proportion of vegetation cover on the site, at least 85% – 90%. A deep-rooted perennial vegetation cover, typically grasses, forbs, or legumes is recommended to facilitate infiltration and assist with erosion control. This may be satisfied by minimizing the impact to existing vegetation, or may be facilitated by seeding. Crop production may also occur, but additional considerations may be needed to ensure that harvesting does not facilitate increased runoff or erosion. It is also important to promote the establishment of more shade-tolerant vegetation under the panels. Minimal mowing, pesticide, or herbicide application is recommended.

The additional practice recommended in some cases is structural stormwater management. As noted above, these sorts of structural practices may be required for specific cases where a site has a high slope or poorly draining soils. Some structural practices are focused on runoff volume reduction via enhanced infiltration, and include features like infiltration basins or infiltration trenches. Other structural practices may be focused on erosion prevention and sediment control and involve stone drip or splash pads near the dripline area under solar panel rows.

5. Discussion and conclusions

5.1. Insights from ecohydrologic research on solar farms

There is a small but growing body of work characterizing how solar farm development changes soil properties, vegetation, and hydrologic processes. Most existing work focuses on soil properties, vegetation, soil water, and micrometeorological characteristics or evapotranspiration; there is no published work yet in the academic literature, to our knowledge, documenting the direct measurement of runoff on solar farms.

The results of scientific research vary from findings of no net impact of solar farms on these ecohydrological properties to detection of some impacts. Field soil moisture measurements often demonstrated variability with respect to the solar panels. These changes in soil moisture relative to panels demonstrate the impact of panels on solar radiation, runoff redistribution, and the corresponding evapotranspiration. Particularly in regions where evapotranspiration is not energy-limited (e.g. warm arid regions), there is a climatic sweet spot where the shading of solar panels can help reduce evapotranspiration and maximize water efficiency and facilitate enhanced crop production in association with solar farms (Barron-Gafford *et al* 2019, Hassanpour Adeh *et al* 2018). Results from agrivoltaic systems indicate that crops can still achieve high yield under the fluctuating shade of these systems (Marrou *et al* 2013a). However, more extensive research is merited in agrivoltaic systems across a range of climate settings and crop types.

In wetter climates, there is an interest in keeping soils from reaching sustained levels of saturation and the associated runoff generation. Solar panels introduce heterogeneity in the soil moisture distribution, with precipitation accumulating along the dripline at the lower edge of the panels. It is essential that appropriate management practices are implemented to prevent this heterogeneity from manifesting in increased runoff and erosion generation. Variable panel tilting may also be considered to reduce the redistribution of water.

Table 3. Example guidelines from US states regarding stormwater management on solar farms. The table is not comprehensive of every guideline for all listed states, but provides examples of the range of guidelines currently available.

Category	Recommendation	Source of example
	Site conditions	
Site slope	Ideally <5%; >5% requires various additional management considerations. For slopes >8%, additional management needed to maintain sheet flow and prevent erosion. <10% is favorable; additional management considerations if >10%.	Maryland (MA DOE 2021) North Carolina (NC DEQ 2018), Rhode Island (RI DEM 2021) Pennsylvania (PA DEP, 2019)
Soils	For soils with a depth to bedrock of 12″ or less, plans must show that soil will be enhanced by the addition of at least 4″ of top soil.	New Hampshire (NH DES 2020)
	Sites with soils having a slip potential should be more closely evaluated for any geotechnical issues—especially in areas with moderate to steep slopes. 2. Soil compaction should be avoided.	Pennsylvania
	Considerations during construction	
Considerations during construction	To minimize disturbance and compaction, construction vehicles and equipment should avoid interspace areas during installation of the solar panels to effectively use interspace later for impervious disconnection/infiltration.	Maryland
	Erosion and sediment control practices are needed. Temporary erosion control, such as mulch, must be put on exposed soil at the site to prevent erosion during rain events until vegetation is established.	Massachusetts (Mass DEP 2017), Minnesota (MN PCA, 2021), New Hampshire
	Avoid soil compaction and/or topsoil removal. Ifthe soil is compacted or removed, it should be amended to return to its pre-development condition.	Massachusetts, New Hampshire, North Carolina
	Post-construction stormwater management	
Modeling runoff from impervious area	The calculation of water quality volume depends on the slope (if >15%, then panels are an effective impervious area, if not then the evaluation of vegetated areas is emphasized).	Connecticut (CT DEEP 2020)
	For water quality and water quantity calculations, solar panels are considered disconnected impervious surfaces.	Minnesota, Virginia (VA DEQ 2022)
	Curve number adjustment is permitted to account for infiltration under impervious panels. With certain steeper slope + soil drainage classes, there cannot be the assumption that infiltration will occur under panels.	New Hampshire
	Solar panels are not considered impervious surfaces, so they do not need to be considered in the calculation of impervious cover at a site.	New Jersey (New Jersey Legislature 2021)
Panel orientation	Parallel orientation of the solar panels is recommended with respect to slope, in order to prevent flow concentration. If not, runoff should be directed to infiltration practices.	Rhode Island
	The orientation of panels should be considered with respect to drainage pattern, flow concentration, drainage area, and velocity.	Connecticut
Vertical clearance of panels	< 10 feet in order to minimize erosion at the dripline.	Connecticut, Massachusetts, North Carolina, Ohio (OH EPA 2019), Pennsylvania
Impervious disconnection	In general, all states with solar-specific stormwater guidance leverage the disconnection of the impervious surface (i.e., solar panel rows) with well-established vegetation as a key stormwater management strategy, under certain site conditions. More details are noted in the examples below.	
	The vegetated interspace area receiving runoff must be equal to or greater in length than the disconnected surface (e.g., the width of the row of solar panels). Runoff must sheet flow onto and across vegetated areas to maintain the disconnection.	Maryland, North Carolina, Pennsylvania, Rhode Island
	Solar panel rows are spaced in a manner to allow sunlight penetration sufficient to support vegetation between the solar panel rows.	Massachusetts, Rhode Island
	Pervious space is required between rows of panels. This allows for the use of the 'disconnected impervious credit method', which often results in a reduction in the water treatment volume required.	Minnesota
	Under some conditions such as the existence of an uncompacted soil profile, dense and healthy vegetation maintenance, it is possible to easily manage the runoff from panels by disconnection. The disconnection length depends on the soil type, where well-draining soils require a shorter interspace (e.g. 1:1 solar panel to interspace distance along the slope) compared to more poorly draining soils.	Ohio

(*continued on next page*)

Table 3. Continued Example guidelines from US states regarding stormwater management on solar farms. The table is not comprehensive of every guideline for all listed states, but provides examples of the range of guidelines currently available.

Category	Recommendation	Source of example
	Site conditions	
Vegetation	In areas receiving disconnected runoff, groundcover vegetation must be maintained in good condition and should be protected from future compaction (e.g., by planting shrubs or trees along the perimeter).	Maryland
	Include cool-season, warm-season, shade-resistant, and legumes as necessary to develop a dense, year-round groundcover that accounts for differences in the temperature and shading from panels.	North Carolina, Ohio, Rhode Island
	Utilize low- and slow-growing grass varieties to reduce compaction and damage from frequent mowing. Low maintenance grass mixture recommended. The use of fertilizers, pesticides, and herbicides should be minimized.	North Carolina, Ohio, Rhode Island
	>90% deep-rooted perennial vegetative cover with a density capable of resisting accelerated erosion and sedimentation is required. If mowed, do not cut to < 4 in. In agrivoltaic applications, this may include hand-harvested or small machine-harvested crops.	Pennsylvania
	There should be at least 85% coverage. Maintain the vegetation height that maximizes sheet flow - no shorter than 4″ and not taller than 12″ (grass) or 18″ (meadow).	Rhode Island
Post-construction structural stormwater management	When the slope >5%, spreaders, terraces, or berms may be used to prevent concentrated flow and promote infiltration. When the slope >10%, more extensive stormwater management is required.	Maryland
	If the disconnected interspace is not adequate for the volume reduction of runoff or other site conditions merit it, other types of permanent stormwater management for non-erosive conveyance of runoff must be constructed, such as infiltration trenches or berms, wet sedimentation basins, or sand filters.	Connecticut, Massachusetts, Minnesota, Pennsylvania
	A stone drip pad to prevent erosion at the dripline, if panels have a fixed inclination.	Ohio
	Where panels are not oriented generally parallel with the slope and/or where slopes are >8%, runoff needs to be either intercepted by stone trenches for infiltration and/or directed non-erosively to an infiltration practice. Add scour control if instances of erosion/scour develop. Regular inspection and maintenance of infiltration practices is required, and to look for erosion	Rhode Island
	For a solar array in an open field, it is expected that the designer will show compliance with flow control related requirements by using infiltration and/or dispersion type management practices	Washington (Washington State Department of Ecology 2021)

At the time of this review, we 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.

In general, there is still also a need for simultaneous evaluation of multiple environmental co-benefits from solar farm land management, considering how certain vegetation or crop choices could help manage runoff, but also provide habitat or food.

5.2. Connecting observed phenomena to management decisions

While there are some environmental conditions that are linked to the inherent characteristics of ground-mounted solar panels (e.g. that there will be at least some level of shading and interception of water from an inclined panel above the ground), many phenomena can be influenced strongly by specific decisions in how the solar farm is constructed and managed.

Changes in certain soil properties (e.g. the reduction in soil organic matter) between solar farms and reference sites indicate the impacts of initial solar farm development, such as some removal of soil and/or vegetation and regrading of soil. This is something that can be changed by a more careful development process. Other soil property changes in different parts of the solar farm (under panel versus interspace) indicate the impacts of continued maintenance between the panels, such as mowing, that may induce some compaction. Thus, these observed detrimental impacts should be addressed as solar farm development guidance is developed. There are opportunities to select management practices that minimize adverse impacts (e.g. soil compaction) and maximize additional benefits- for example, leveraging sheep grazing for vegetation management in lieu of frequent mowing.

5.3. Key gaps in regulatory/management approaches and scientific knowledge

Most states in the US currently rely on construction general permits for guiding solar farm development, which may not be adequate for the unique design of solar farms (Great Plains Institute 2021). Only 12 of 50 US states had solar-specific stormwater management guidance, as of the writing of this review. The management practices currently recommended largely leverage low impact development practices of disconnection of the solar panel impervious surface, well-developed shade-tolerant vegetation, and minimal impact of construction practices on soil properties. Where necessary, given site conditions or solar panel configuration, structural stormwater practices such as infiltration practices are recommended. These recommendations are an important start, but validation is needed to confirm that these current practices are adequate, and appropriately tailored to the site conditions. There is a particular lack of guidance relating to appropriate stormwater management practices for solar farms in arid environments (table 3).

Given that runoff volume and quality are key metrics in the stormwater regulatory realm, it is a major gap that there is a lack of field research studying runoff on solar farms. It is also critical that hydrologic modeling approaches be improved to appropriately represent the unique design of solar panels, in that there is an impervious surface with the ability to infiltrate water underneath. In particular, approaches are needed that are simple enough to be widely implemented by those personnel preparing runoff calculations and associated permits for proposed solar farm development.

Though this review focused on hydrology and stormwater management, it is critical that future research and management consider simultaneous evaluation of some of the many other ecosystem services (or disservices) that could be provided by solar farms (Moore-O'Leary *et al* 2017). The role of solar farms (and how precisely they are developed) can also be explored further within the food-energy-water nexus (Lee *et al* 2021). Hernandez *et al* recently proposed a framework of 'techno-ecological synergy' which pushes us to think more broadly about how to implement renewable energy technologies where they will minimize ecological impact and maximize additional co-benefits (Hernandez *et al* 2019). Thus, instead of simply considering how to minimize the environmental impacts for an already proposed solar farm, we need to also think more broadly about what are the most optimal sites for this type of development. This includes considering how to leverage existing impervious surface for the implementation of utility-scale solar energy, such as parking lots or warehouses. With these multi-criteria and system frameworks, we can ensure that solar farms are developed in the most sustainable manner.

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Data availability statement

No new data were created or analysed in this study.

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