APPENDIX U

Hydrology
Technical Memorandum

Kimley»Horn

MEMORANDUM

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Date: 04/08/21

Subject: Hydrology Technical Memorandum – JVR Energy Project

Public comments were received on the JVR Energy Park Draft Environmental Impact Report (EIR) regarding hydrology. This technical memorandum provides information regarding issues raised in the comments, including the photovoltaic (PV) panel height and Proposed Project impervious surfaces.

Photovoltaic (PV) Panel Height
Comments were received regarding the height of the proposed PV panels (aka modules). Commenters stated the panel height should be lower. As described in Chapter 1 of the Draft EIR, the height of the panels would be 12 feet. The height of the tops of panels above grade at full tilt is estimated to reach up to 12 feet due to the following factors, driven up primarily by flood depths within the development footprint, as depicted on Figure KH-EIR-PR-01.

1) Topographic Undulation: Single Axis Tracker (SAT) racking systems as proposed for the Proposed Project support many panels together in a straight line across hundreds of feet to track the sun throughout the day. The tops of these rigid trackers are straight in order to connect panels together. However, the natural grade beneath the trackers undulates up and down. In order to place rigid trackers on natural grade without blade-leveling the entire site into a planar surface, piles are used to accommodate the undulating terrain below. In doing so, the Proposed Project greatly reduces earthwork operations and minimizes impacts to natural drainage patterns. For example, at least an average of 12 inches of grade undulation tolerance should be provided to accommodate small undulations in the terrain while other larger undulations will be resolved

with grading activities. This tolerance is considered in addition to any minimum heights that are based on mechanical dimensions of the racking system and may result in taller panel heights that would otherwise be required at a given pile location. It is generally expected that low spots will also have flood depths up to the maximum allowable depths noted herein and therefore this factor does not necessarily determine the maximum panel heights, but it explains why trackers may have taller heights than otherwise expected at a given location.

2) Racking Height: The SAT racking system itself has its own minimum mechanical heights for installation, operation, and maintenance as dictated by the manufacturer. At the ideal location where ground is level (not a low spot) and flood depths are minimal (6 inches or shallower), the anticipated Project racking system minimum mechanical height is about 4.6 feet as measured from the ground top of panel in its flat position (no tilt) and about 7.5 feet to the top of panel in its full-tilt position.

3) Flood Depths: Due to a large offsite upstream tributary area of over 100 square miles, substantial flows concentrate and pass through the Proposed Project development footprint and generate on-site flooding up to 5 feet deep within the Proposed Project perimeter fence for the 100-year design storm (Base Flood) event as shown in Figure 8 of the Preliminary Drainage Study prepared by Kimley-Horn (August, 2020). The Drainage Study is included as Appendix I to the EIR. (See also Draft EIR, Section 2.7.3.2 noting that average flood depths in a 100-year flood event across the Project site are 2-3 feet). This depth is based on the analysis of the site assuming that breakaway fencing will be used. Per the San Diego County Flood Damage Prevention ordinance and guidance from the Federal Emergency Management Agency (FEMA), panels and other electrical equipment that cannot satisfy required waterproof ratings must be elevated to provide at least 12 inches of freeboard as a factor of safety above the calculated Base Flood Elevation (BFE; the calculated water surface elevation generated by the 100-year storm) for any given location. This is also incorporated as Project Design Feature PDF-HYD-1.

4) Panel Dimensions: The panels proposed for this Proposed Project are expected to measure approximately 7.5 feet long. The leading (bottom) edge of panels must be elevated above design flood depths by the required freeboard while they rotate throughout the day to track the sun. At a rotation angle (aka Range of Motion or ROM) of 52 degrees relative to horizontal for the SAT racking system, the panels measure about 6 feet high at full tilt. The Proposed Project has been designed around the mainstream panels available during the construction period. In general, available utility-scale panels range from 6.5 feet to 7.9 feet long. The shortest panels are in the 410w range and facing obsolescence. By using a slightly larger module, the Proposed Project obtains ~530W per panel, and therefore reduces project footprint from an infeasible size to a feasible size. Also, please note that panels are mounted on the racking system in a portrait orientation (long end perpendicular to axis of rotation) as is standard practice and rotating the panels to landscape orientation would require twice as much racking, piles, and other equipment that would make the Proposed Project infeasible.

These environmental and mechanical conditions are not adjustable; therefore, it is not possible to reduce maximum height of the panels to between 6 to 8 feet as requested by a commenter. However, please note that the maximum height of 12 feet represents the full-tilt position and that same tracker would be 9 feet tall in the flat position. Furthermore, that 12-foot max height is based on the combination of all criteria above and is not expected to represent the typical height across the entire Proposed Project site. Where conditions are favorable, panels may be as short as 7.5 feet in the full-tilt position and 4.6 feet in the flat position. Actual heights vary by location based on terrain and flood depths.

Additional hydrologic and hydraulic analyses will be performed pursuant to mitigation measure **M-HYD-1** to demonstrate that that the design features for the perimeter fencing avoids the blockage and/or redirection of storm flows resulting from the accumulation of debris/detritus at wash crossings.

Additionally, a commenter draws comparison to an existing solar facility referred to as “Borrego Solar Farm” located in San Diego County as having highest points of 6 to 8 feet above grade and requests an explanation of why such heights cannot be used on the Proposed Project. Kimley-Horn assumes this is referring to the facility permitted through the County under MUP 3300-10-026, EIR No. 3910-10-050-001 and built in 2013 by NRG. The Borrego facility is located in unincorporated San Diego County just north of Borrego Springs, southwest of the intersection of Borrego Valley Road and Henderson Canyon Road, about 45 miles north of the Proposed Project. Although both the Borrego facility and the Proposed Project will use Single-Axis-Tracker (SAT) racking systems, these three main differences between the two facilities can explain the discrepancy in max panel heights:

1) <u>Terrain:</u> The Borrego site was much flatter than the Project site and thus did not require the additional pile reveal (and subsequently taller panels) to accommodate ground undulations as is required for this Proposed Project. This makes sense as Borrego Springs is a flatter and wider valley compared to the more hilly terrain of Jacumba Hot Springs.

2) <u>Flood Depths:</u> The Borrego site has less upstream offsite tributary area that discharges storm runoff onto the site where FEMA has estimated flood depths to be about one foot per Figure KH-EIR-PR-02. By contrast, the Proposed Project site that has over 100 square miles of tributary watershed area concentrating and draining through it, generating flood depths up to five feet with no feasible diversion or containment options to prevent that run-on from impacting the PV array field and forcing the design to raise equipment.

3) <u>Panel Dimensions:</u> It is also likely that the panels (aka modules) used 7 years ago were smaller in dimension and lower in power generation ratings, which also could have contributed to reduced heights. Detailed review of the site or plans would be required to make these comparisons and the Proposed Project does not have access to the Borrego site.

For additional comparison, Granger Solar was another SAT solar farm within San Diego County (PDS2015-MUP-15-019 approved on 2/26/16) and it proposed panel heights of up to 12 feet tall, primarily to accommodate severe undulating terrain on a hilltop. Therefore, it should be recognized that 12 foot proposed maximum panel heights at full tilt are not unreasonable for such facilities.

Proposed Project Impervious Surfaces

Comments were received stating the solar panels should be analyzed as impervious surfaces. The Proposed Project lies east of the Salton Sea divide, within Regional Water Quality Control Board (RWQCB) Region 7, which requires a Standard Project Storm Water Quality Control Plan (SWQMP) for all development projects. Standard Project SWQMPs do not require quantification of stormwater runoff for pollutant control or hydromodification management purposes, therefore the amount of impervious surfaces would not affect any of the requirements or impacts in the Proposed Project's Standard Project SWQMP.

In the Drainage Report dated August 2020, Section 5.4 "Proposed Land Use / Land Cover" states that the "Proposed project will produce approximately 1.9 acres (0.0030 square-miles) of impervious area." In responding to comments on the Draft EIR for the Proposed Project, it was determined that this was a miscalculation of the Proposed Project's impervious area; the Proposed Project will produce 6.65 acres of impervious area. A breakdown of the proposed site impervious area is shown below and on the MUP Plot Plan sheet 400.

IMPERVIOUS SURFACES

PV TRACKER PILES	681 SF
INVERTER/TRANSFORMER SKIDS ON PADS	4,000 SF
BATTERY STORAGE CONTAINERS	75,281 SF
PROJECT SUBSTATION GRADED PAD	27,360 SF
SDG&E SWITCHYARD GRADED PAD	127,100 SF
AC DRIVEWAYS/PUBLIC IMPROVEMENTS	55,321 SF
TOTAL	289,744 SF 6.65 AC

Site impervious area is important in that it has a direct effect on the amount of runoff generated within a given watershed. The change in impervious area above represents a net gain of 4.75 acres from the total impervious area described in the Drainage Report from August 2020. In relationship to the Project and watershed footprints, this increase in imperviousness is insignificant. The revised impervious area of 6.65 acres (0.1004 mi^2) will comprise only 0.09% of the 111 mi^2 watershed and only 1.1% of the 623 acre proposed Project site. This value is too low to trigger a change in on-site runoff Curve Number values for proposed conditions analysis, therefore no changes are required to the calculations or analysis summarized in the Drainage Study. The Drainage Study's conclusion that the increase in impervious area constitutes a small enough area to confidently assume that the additional impervious area for the solar site will have minimal to no impact on the existing watershed hydrologically remains accurate.

Furthermore, the County agrees with the assumptions of impervious areas used in the Drainage Study to analyze the hydrologic and hydraulic impacts of the Proposed Project. It is consistent with analysis provided by other solar projects in the area that have been approved by the County.

The general industry and municipal consensus has been that the addition of photovoltaic solar panels does not increase runoff from solar facilities. In principal, this is because while the panels may cover a vast area, they do not cover the actual natural surfacing underneath them. The only improvement structure to come in contact with the ground on the Single Axis Tracker (SAT) racking system (such as that proposed for the Proposed Project) are the driven piles (aka piers) that support them. As shown on the Proposed Project plot plans, the piles make up a relatively small impervious area (about 681 square feet, or 0.016 acres), and comprise a small percentage of both the total impervious area for the site of 6.65 acres (0.24%), and of the total solar facility development footprint area of 623 acres (0.0025%). Because the support piles are the only improvement on a solar tracker to come into contact with the underlying natural surfacing, rainfall is shed off panels and onto the natural ground below where it is free to infiltrate and move as surface flow, similar to existing conditions. See Section 5.4 of the Drainage Study prepared by Kimley-Horn (August 2020) for more information.

The comments also refer to a study by Cook and McCuen titled *Hydrologic Response of Solar Farms* available from the American Society of Civil Engineers (ASCE) and published in 2013 (attached), which attempts to "determine the hydrologic effects of solar farms". The study does conclude that the peak discharge can increase in instances where gravel or pavement is placed under panels. This is indicative of some solar farms developed in extremely arid and sterile climates where revegetating the ground below panels is not feasible or not preferred and instead the site is compacted, treated with chemical dust suppressant (albeit often permeable) or soil stabilizers to minimize dust. For instance, such methods were proposed for the 26 MW Borrego Solar I facility built in 2013 located 45 miles north of the Project (MUP 3300-10-026, ER No. 3910-10-050-001).

However, the Proposed Project will not be paved under the PV trackers for post-construction stabilization. Instead, the Proposed Project will apply permanent seeding to stabilize the soil and provide vegetative cover under the solar panels during Project operations. The vegetative cover requirement is addressed in Project Design Feature PDF-HYD-3 in the Final EIR and is shown on the MUP Plot Plan. During construction, temporary Best Management Practices (BMPs) will be implemented to minimize sediment discharge from the site through the Stormwater Pollution Prevention Plan (SWPPP) subject to State of California Water Board jurisdiction per the Environmental Protection Agency (EPA).

The study concludes that "The addition of solar panels over a grassy field does not have much of an effect on the volume of runoff, the peak discharge, nor the time to peak". The Proposed Project will much more closely follow this scenario as compared to the scenario of paving or leaving bare soil under the panels. Therefore, it is the assertion of this technical memorandum that solar panels for the Proposed Project, located east of the Salton Sea divide, should not be viewed as impervious and that the Proposed Project would not substantially increase runoff.

A comment on the Draft EIR also cites the State of Minnesota Stormwater Manual (MNSWM) in quoting a potential 15-50% increase in runoff volume may be caused by installing PV panels. However, based on the fact that runoff from panels infiltrates into the soil below all panels, Kimley-

Horn reaffirms the assertion of panels as pervious area for the Proposed Project for the purposes of calculating stormwater runoff leaving the site.

Concerns were also raised by commenters on the Draft EIR about potential localized erosion and/or scour due to runoff from the leading edge of panels, again citing the MNSWM. The MNSWM Fact Sheet on Stormwater Guidance for Solar Farm Projects cites this as “one of the most notable impacts of solar sites on water quality” and that “the Minnesota Pollution Control Agency (MPCA) recommends the lowest vertical clearance of any solar array be no greater than 10 feet in order to prevent/control erosion and scour along the dripline” and that “If elevation is greater than 10 feet, BMPs would be necessary to prevent/control erosion and scour along the drip line". The commenter also notes that “a solar PV development site stripped of vegetation may result in erosive stormwater flows”.

As explained in the discussion above under PV Panel, the PV panels will range from 4.6 to 9 feet above grade in the flat position, with the leading edge of panels at 1.5 to 6.5 feet above grade at full tilt, and the top of the panels at 7.5 to 12 feet above grade at full tilt, depending on location. Furthermore, the Proposed Project’s Single Axis Tracker (SAT) racking system will gradually tilt panels throughout the day, so rainfall that hits them will be shed across a 1.5 foot wide swath of ground on each side of the tracker depending on time of day. Comparatively, Fixed-Tilt racking systems are larger and concentrate more runoff to a fixed point on the ground for their entire service life. It is inappropriate to attribute worst-case erosion assumptions to SAT racking systems for this reason. Because equipment is dynamic and lower than the MPCA suggested thresholds, BMPs are not necessarily required. However, PDF-HYD-3 requires permanent 70% vegetation cover restoration compared to pre-development conditions. Therefore, drip line erosion concerns will be adequately addressed by the Proposed Project.

Please do not hesitate to reach out with any further questions to clarify the responses herein.

Sincerely,

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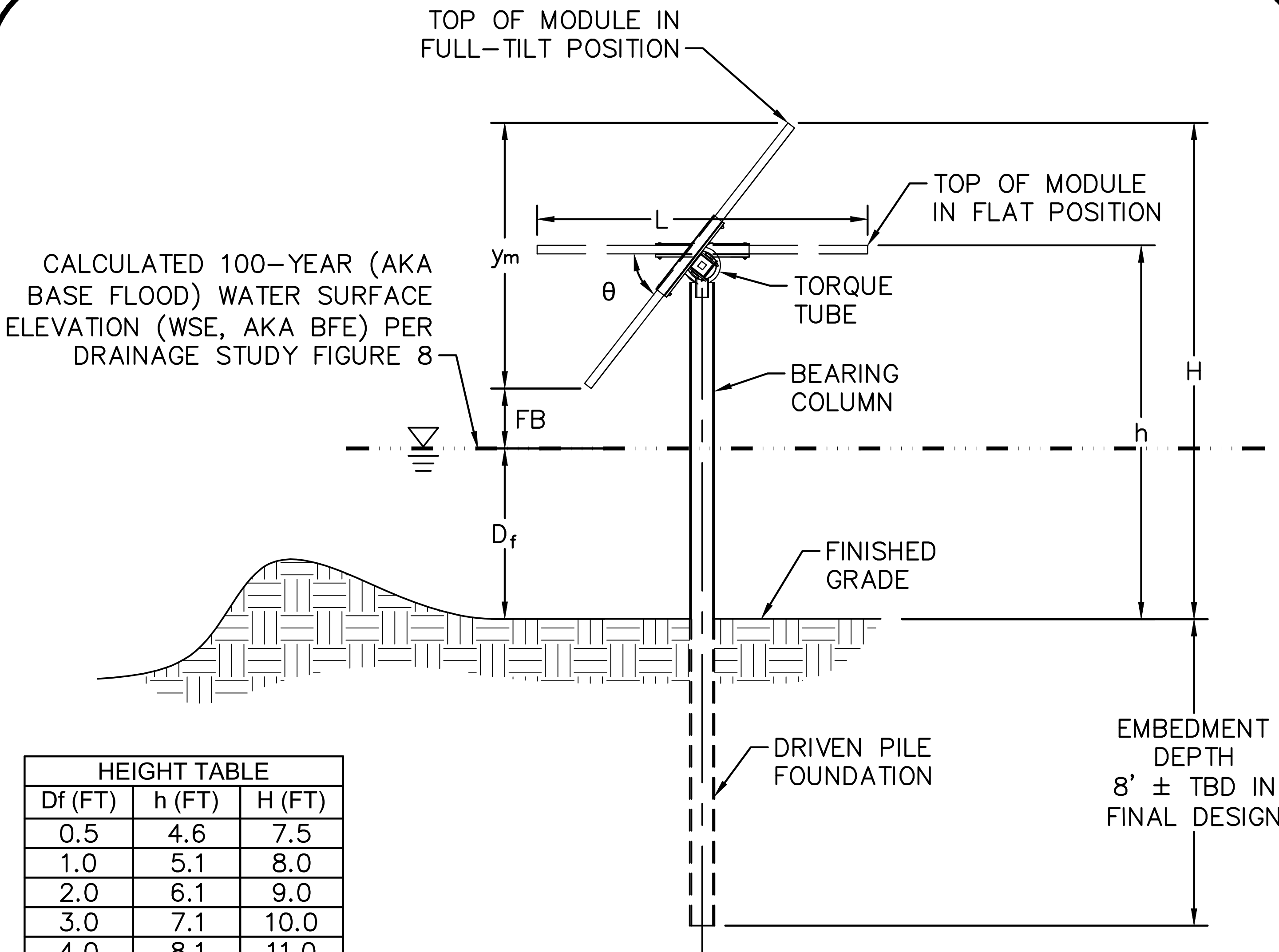

HEIGHT TABLE		
Df (FT)	h (FT)	H (FT)
0.5	4.6	7.5
1.0	5.1	8.0
2.0	6.1	9.0
3.0	7.1	10.0
4.0	8.1	11.0
5.0	9.1	12.0

PROJECT SPECIFICATIONS:

- D_f ≈ 5.0'MAX — BASE FLOOD DEPTH PER DRAINAGE REPORT FIGURE 8
- FB = 1.0' — FREEBOARD FOR ELECTRICAL EQUIPMENT (INCLUDING MODULES)
- L ≈ 7.5' — MODULE LENGTH
- θ = 52° — TRACKER ROTATION ANGLE AT FULL–TILT
- y_m ≈ 5.9' — MODULE HEIGHT AT FULL–TILT ($L \cdot \sin\theta$)

NOTES:

1. PROPOSED PROJECT WILL UTILIZE SINGLE AXIS TRACKER (SAT) RACKING SIMILAR TO THAT SHOWN HEREON
2. PILE HEIGHTS NOTED IN TABLE ARE MINIMUMS FOR FLOOD DEPTH AND ARE SUBJECT TO CHANGE DURING FINAL DESIGN
3. PILE HEIGHTS MUST ALSO FLUCTUATE TO ACCOMMODATE GROUND UNDULATIONS UNDERNEATH TRACKER WHILE HOLDING THE TORQUE TUBE AT A CONSISTENT SLOPE; THIS COULD RESULT IN PILE HEIGHTS GREATER THAN THE MINIMUM PER FLOOD DEPTHS ALONE AT A GIVEN PILE LOCATION BUT WILL NOT EXCEED THE SITE MAXIMUM HEIGHT OF 12–FEET NOTED HEREON BASED ON PRELIMINARY DRAINAGE ANALYSIS.

PRELIM TRACKER HEIGHT TYPICAL SECTION

CREATED BY: WHC MODIFIED: 04/06/2021

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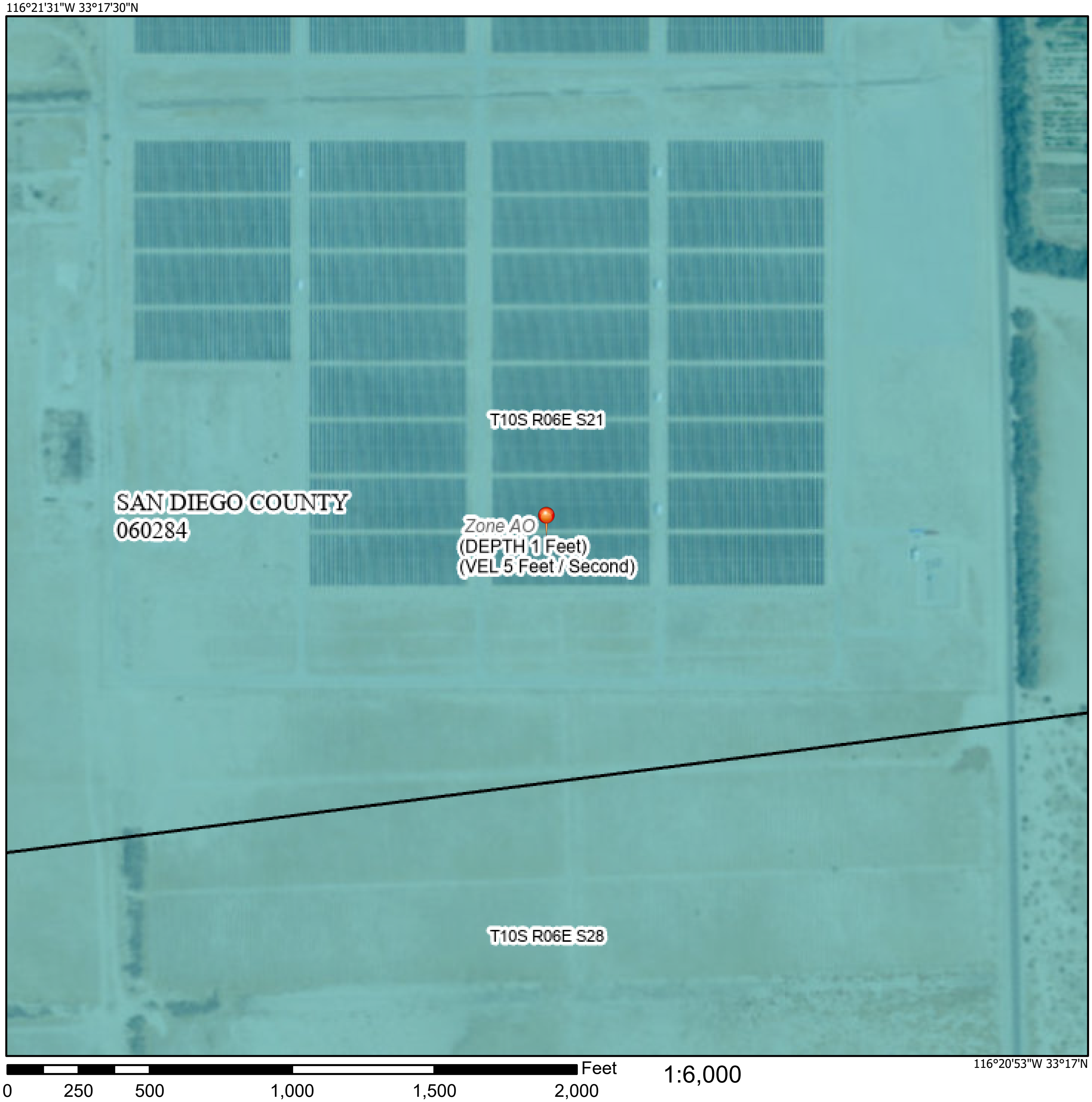
National Flood Hazard Layer FIRMette

FEMA

FIGURE KH-EIR-PR-02



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Legend

SEE FIS REPORT FOR DETAILED LEGEND AND INDEX MAP FOR FIRM PANEL LAYOUT

SPECIAL FLOOD HAZARD AREAS
- Without Base Flood Elevation (BFE) *Zone A, V, A99*
- With BFE or Depth *Zone AE, AO, AH, VE, AR*
- Regulatory Floodway

OTHER AREAS OF FLOOD HAZARD
- 0.2% Annual Chance Flood Hazard, Areas of 1% annual chance flood with average depth less than one foot or with drainage areas of less than one square mile *Zone X*
- Future Conditions 1% Annual Chance Flood Hazard *Zone X*
- Area with Reduced Flood Risk due to Levee. See Notes. *Zone X*
- Area with Flood Risk due to Levee *Zone D*

OTHER AREAS
- NO SCREEN Area of Minimal Flood Hazard *Zone X*
- Effective LOMRs
- Area of Undetermined Flood Hazard *Zone D*

GENERAL STRUCTURES
- Channel, Culvert, or Storm Sewer
- Levee, Dike, or Floodwall

OTHER FEATURES
- 20.2 / 17.5 Cross Sections with 1% Annual Chance Water Surface Elevation
- 8 Coastal Transect
- 513 Base Flood Elevation Line (BFE)
- Limit of Study
- Jurisdiction Boundary
- Coastal Transect Baseline
- Profile Baseline
- Hydrographic Feature

MAP PANELS
- Digital Data Available
- No Digital Data Available
- Unmapped

N

The pin displayed on the map is an approximate point selected by the user and does not represent an authoritative property location.

This map complies with FEMA's standards for the use of digital flood maps if it is not void as described below. The basemap shown complies with FEMA's basemap accuracy standards

The flood hazard information is derived directly from the authoritative NFHL web services provided by FEMA. This map was exported on 1/9/2021 at 3:41 AM and does not reflect changes or amendments subsequent to this date and time. The NFHL and effective information may change or become superseded by new data over time.

This map image is void if the one or more of the following map elements do not appear: basemap imagery, flood zone labels, legend, scale bar, map creation date, community identifiers, FIRM panel number, and FIRM effective date. Map images for unmapped and unmodernized areas cannot be used for regulatory purposes.

Hydrologic Response of Solar Farms

Lauren M. Cook, S.M.ASCE[1]; and Richard H. McCuen, M.ASCE[2]

Abstract: Because of the benefits of solar energy, the number of solar farms is increasing; however, their hydrologic impacts have not been studied. The goal of this study was to determine the hydrologic effects of solar farms and examine whether or not storm-water management is needed to control runoff volumes and rates. A model of a solar farm was used to simulate runoff for two conditions: the pre- and postpaneled conditions. Using sensitivity analyses, modeling showed that the solar panels themselves did not have a significant effect on the runoff volumes, peaks, or times to peak. However, if the ground cover under the panels is gravel or bare ground, owing to design decisions or lack of maintenance, the peak discharge may increase significantly with storm-water management needed. In addition, the kinetic energy of the flow that drains from the panels was found to be greater than that of the rainfall, which could cause erosion at the base of the panels. Thus, it is recommended that the grass beneath the panels be well maintained or that a buffer strip be placed after the most downgradient row of panels. This study, along with design recommendations, can be used as a guide for the future design of solar farms. **DOI: 10.1061/(ASCE)HE.1943-5584.0000530.** *© 2013 American Society of Civil Engineers.*

CE Database subject headings: Hydrology; Land use; Solar power; Floods; Surface water; Runoff; Stormwater management.

Author keywords: Hydrology; Land use change; Solar energy; Flooding; Surface water runoff; Storm-water management.

Introduction

Storm-water management practices are generally implemented to reverse the effects of land-cover changes that cause increases in volumes and rates of runoff. This is a concern posed for new types of land-cover change such as the solar farm. Solar energy is a renewable energy source that is expected to increase in importance in the near future. Because solar farms require considerable land, it is necessary to understand the design of solar farms and their potential effect on erosion rates and storm runoff, especially the impact on offsite properties and receiving streams. These farms can vary in size from 8 ha (20 acres) in residential areas to 250 ha (600 acres) in areas where land is abundant.

The solar panels are impervious to rain water; however, they are mounted on metal rods and placed over pervious land. In some cases, the area below the panel is paved or covered with gravel. Service roads are generally located between rows of panels. Altlhough some panels are stationary, others are designed to move so that the angle of the panel varies with the angle of the sun. The angle can range, depending on the latitude, from 22° during the summer months to 74° during the winter months. In addition, the angle and direction can also change throughout the day. The issue posed is whether or not these rows of impervious panels will change the runoff characteristics of the site, specifically increase runoff volumes or peak discharge rates. If the increases are hydrologically significant, storm-water management facilities may be needed. Additionally, it is possible that the velocity of water draining from the edge of the panels is sufficient to cause erosion of the soil below the panels, especially where the maintenance roadways are bare ground.

The outcome of this study provides guidance for assessing the hydrologic effects of solar farms, which is important to those who plan, design, and install arrays of solar panels. Those who design solar farms may need to provide for storm-water management. This study investigated the hydrologic effects of solar farms, assessed whether or not storm-water management might be needed, and if the velocity of the runoff from the panels could be sufficient to cause erosion of the soil below the panels.

Model Development

Solar farms are generally designed to maximize the amount of energy produced per unit of land area, while still allowing space for maintenance. The hydrologic response of solar farms is not usually considered in design. Typically, the panels will be arrayed in long rows with separations between the rows to allow for maintenance vehicles. To model a typical layout, a unit width of one panel was assumed, with the length of the downgradient strip depending on the size of the farm. For example, a solar farm with 30 rows of 200 panels each could be modeled as a strip of 30 panels with space between the panels for maintenance vehicles. Rainwater that drains from the upper panel onto the ground will flow over the land under the 29 panels on the downgradient strip. Depending on the land cover, infiltration losses would be expected as the runoff flows to the bottom of the slope.

To determine the effects that the solar panels have on runoff characteristics, a model of a solar farm was developed. Runoff in the form of sheet flow without the addition of the solar panels served as the prepaneled condition. The paneled condition assumed a downgradient series of cells with one solar panel per ground cell. Each cell was separated into three sections: wet, dry, and spacer.

The dry section is that portion directly underneath the solar panel, unexposed directly to the rainfall. As the angle of the panel from the horizontal increases, more of the rain will fall directly onto

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the ground; this section of the cell is referred to as the wet section. The spacer section is the area between the rows of panels used by maintenance vehicles. Fig. 1 is an image of two solar panels and the spacer section allotted for maintenance vehicles. Fig. 2 is a schematic of the wet, dry, and spacer sections with their respective dimensions. In Fig. 1, tracks from the vehicles are visible on what is modeled within as the spacer section. When the solar panel is horizontal, then the length longitudinal to the direction that runoff will occur is the length of the dry and wet sections combined. Runoff from a dry section drains onto the downgradient spacer section. Runoff from the spacer section flows to the wet section of the next downgradient cell. Water that drains from a solar panel falls directly onto the spacer section of that cell.

The length of the spacer section is constant. During a storm event, the loss rate was assumed constant for the 24-h storm because a wet antecedent condition was assumed. The lengths of the wet and dry sections changed depending on the angle of the solar panel. The total length of the wet and dry sections was set

Fig. 1. Maintenance or "spacer" section between two rows of solar panels (photo by John E. Showler, reprinted with permission)

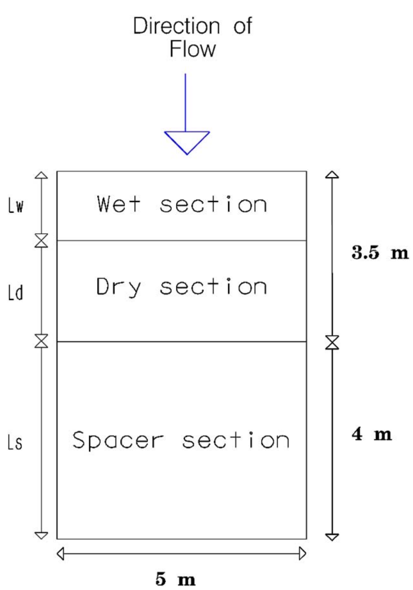

Fig. 2. Wet, dry, and spacer sections of a single cell with lengths *Lw*, *Ls*, and *Ld* with the solar panel covering the dry section

equal to the length of one horizontal solar panel, which was assumed to be 3.5 m. When a solar panel is horizontal, the dry section length would equal 3.5 m and the wet section length would be zero. In the paneled condition, the dry section does not receive direct rainfall because the rain first falls onto the solar panel then drains onto the spacer section. However, the dry section does infiltrate some of the runoff that comes from the upgradient wet section. The wet section was modeled similar to the spacer section with rain falling directly onto the section and assuming a constant loss rate.

For the presolar panel condition, the spacer and wet sections are modeled the same as in the paneled condition; however, the cell does not include a dry section. In the prepaneled condition, rain falls directly onto the entire cell. When modeling the prepaneled condition, all cells receive rainfall at the same rate and are subject to losses. All other conditions were assumed to remain the same such that the prepaneled and paneled conditions can be compared.

Rainfall was modeled after an natural resources conservation service (NRCS) Type II Storm (McCuen 2005) because it is an accurate representation of actual storms of varying characteristics that are imbedded in intensity-duration-frequency (IDF) curves. For each duration of interest, a dimensionless hyetograph was developed using a time increment of 12 s over the duration of the storm (see Fig. 3). The depth of rainfall that corresponds to each storm magnitude was then multiplied by the dimensionless hyetograph. For a 2-h storm duration, depths of 40.6, 76.2, and 101.6 mm were used for the 2-, 25-, and 100-year events. The 2- and 6-h duration hyetographs were developed using the center portion of the 24-h storm, with the rainfall depths established with the Baltimore IDF curve. The corresponding depths for a 6-h duration were 53.3, 106.7, and 132.1 mm, respectively. These magnitudes were chosen to give a range of storm conditions.

During each time increment, the depth of rain is multiplied by the cell area to determine the volume of rain added to each section of each cell. This volume becomes the storage in each cell. Depending on the soil group, a constant volume of losses was subtracted from the storage. The runoff velocity from a solar panel was calculated using Manning's equation, with the hydraulic radius for sheet flow assumed to equal the depth of the storage on the panel (Bedient and Huber 2002). Similar assumptions were made to compute the velocities in each section of the surface sections.

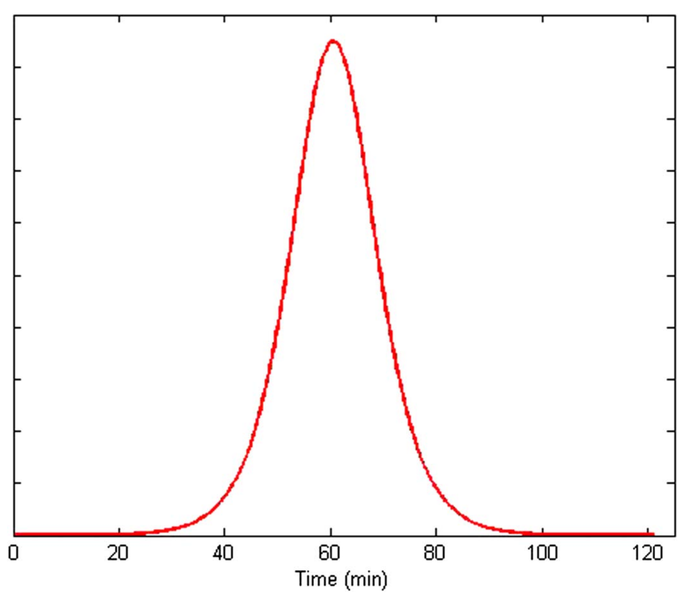

Fig. 3. Dimensionless hyetograph of 2-h Type II storm

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Runoff from one section to the next and then to the next downgradient cell was routed using the continuity of mass. The routing coefficient depended on the depth of flow in storage and the velocity of runoff. Flow was routed from the wet section to the dry section to the spacer section, with flow from the spacer section draining to the wet section of the next cell. Flow from the most downgradient cell was assumed to be the outflow. Discharge rates and volumes from the most downgradient cell were used for comparisons between the prepaneled and paneled conditions.

Alternative Model Scenarios

To assess the effects of the different variables, a section of 30 cells, each with a solar panel, was assumed for the base model. Each cell was separated individually into wet, dry, and spacer sections. The area had a total ground length of 225 m with a ground slope of 1% and width of 5 m, which was the width of an average solar panel. The roughness coefficient (Engman 1986) for the silicon solar panel was assumed to be that of glass, 0.01. Roughness coefficients of 0.15 for grass and 0.02 for bare ground were also assumed. Loss rates of 0.5715 cm/h (0.225 in./h) and 0.254 cm/h (0.1 in./h) for B and C soils, respectively, were assumed.

The prepaneled condition using the 2-h, 25-year rainfall was assumed for the base condition, with each cell assumed to have a good grass cover condition. All other analyses were made assuming a paneled condition. For most scenarios, the runoff volumes and peak discharge rates from the paneled model were not significantly greater than those for the prepaneled condition. Over a total length of 225 m with 30 solar panels, the runoff increased by 0.26 m^3, which was a difference of only 0.35%. The slight increase in runoff volume reflects the slightly higher velocities for the paneled condition. The peak discharge increased by 0.0013 m^3, a change of only 0.31%. The time to peak was delayed by one time increment, i.e., 12 s. Inclusion of the panels did not have a significant hydrologic impact.

Storm Magnitude

The effect of storm magnitude was investigated by changing the magnitude from a 25-year storm to a 2-year storm. For the 2-year storm, the rainfall and runoff volumes decreased by approximately 50%. However, the runoff from the paneled watershed condition increased compared to the prepaneled condition by approximately the same volume as for the 25-year analysis, 0.26 m^3. This increase represents only a 0.78% increase in volume. The peak discharge and the time to peak did not change significantly. These results reflect runoff from a good grass cover condition and indicated that the general conclusion of very minimal impacts was the same for different storm magnitudes.

Ground Slope

The effect of the downgradient ground slope of the solar farm was also examined. The angle of the solar panels would influence the velocity of flows from the panels. As the ground slope was increased, the velocity of flow over the ground surface would be closer to that on the panels. This could cause an overall increase in discharge rates. The ground slope was changed from 1 to 5%, with all other conditions remaining the same as the base conditions.

With the steeper incline, the volume of losses decreased from that for the 1% slope, which is to be expected because the faster velocity of the runoff would provide less opportunity for infiltration. However, between the prepaneled and paneled conditions, the increase in runoff volume was less than 1%. The peak discharge and the time to peak did not change. Therefore, the greater ground slope did not significantly influence the response of the solar farm.

Soil Type

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 prepaneled 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 prepaneled condition.

Panel Angle

Because runoff velocities increase with slope, the effect of the angle of the solar panel on the hydrologic response was examined. Analyses were made for angles of 30° and 70° to test an average range from winter to summer. The hydrologic response for these angles was compared to that of the base condition angle of 45°. The other site conditions remained the same. The analyses showed that the angle of the panel had only a slight effect on runoff volumes and discharge rates. The lower angle of 30° was associated with an increased runoff volume, whereas the runoff volume decreased for the steeper angle of 70° when compared with the base condition of 45°. However, the differences (~0.5%) were very slight. Nevertheless, these results indicate that, when the solar panel was closer to horizontal, i.e., at a lower angle, a larger difference in runoff volume occurred between the prepaneled and paneled conditions. These differences in the response result are from differences in loss rates.

The peak discharge was also lower at the lower angle. At an angle of 30°, the peak discharge was slightly lower than at the higher angle of 70°. For the 2-h storm duration, the time to peak of the 30° angle was 2 min delayed from the time to peak of when the panel was positioned at a 70° angle, which reflects the longer travel times across the solar panels.

Storm Duration

To assess the effect of storm duration, analyses were made for 6-h storms, testing magnitudes for 2-, 25-, and 100-year return periods, with the results compared with those for the 2-h rainfall events. The longer storm duration was tested to determine whether a longer duration storm would produce a different ratio of increase in runoff between the prepaneled and paneled conditions. When compared to runoff volumes from the 2-h storm, those for the 6-h storm were 34% greater in both the paneled and prepaneled cases. However, when comparing the prepaneled to the paneled condition, the increase in the runoff volume with the 6-h storm was less than 1% regardless of the return period. The peak discharge and the time-to-peak did not differ significantly between the two conditions. The trends in the hydrologic response of the solar farm did not vary with storm duration.

Ground Cover

The ground cover under the panels was assumed to be a native grass that received little maintenance. For some solar farms, the area beneath the panel is covered in gravel or partially paved because the panels prevent the grass from receiving sunlight. Depending on the volume of traffic, the spacer cell could be grass, patches of grass, or bare ground. Thus, it was necessary to determine whether or not these alternative ground-cover conditions would affect the runoff characteristics. This was accomplished by changing the Manning's n for the ground beneath the panels. The value of n under the panels, i.e., the dry section, was set to 0.015 for gravel, with the value for the spacer or maintenance section set to 0.02, i.e., bare ground. These can be compared to the base condition of a native grass ($n = 0.15$). A good cover should promote losses and delay the runoff.

For the smoother surfaces, the velocity of the runoff increased and the losses decreased, which resulted in increasing runoff volumes. This occurred both when the ground cover under the panels was changed to gravel and when the cover in the spacer section was changed to bare ground. Owing to the higher velocities of the flow, runoff rates from the cells increased significantly such that it was necessary to reduce the computational time increment. Fig. 4(a) shows the hydrograph from a 30-panel area with a time increment of 12 s. With a time increment of 12 s, the water in each cell is discharged at the end of every time increment, which results in no attenuation of the flow; thus, the undulations shown in Fig. 4(a) result. The time increment was reduced to 3 s for the 2-h storm, which resulted in watershed smoothing and a rational hydrograph shape [Fig. 4(b)]. The results showed that the storm runoff increased by 7% from the grass-covered scenario to the scenario with gravel under the panel. The peak discharge increased by 73% for the gravel ground cover when compared with the grass cover without the panels. The time to peak was 10 min less with the gravel than with the grass, which reflects the effect of differences in surface roughness and the resulting velocities.

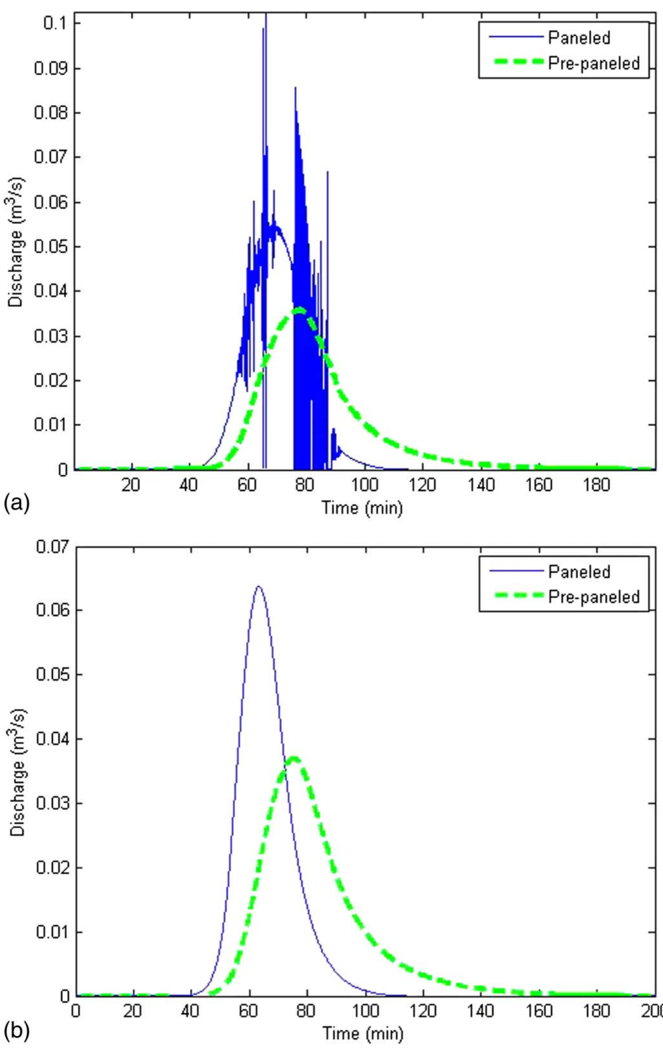

Fig. 4. Hydrograph with time increment of (a) 12 s; (b) 3 s with Manning's n for bare ground

If maintenance vehicles used the spacer section regularly and the grass cover was not adequately maintained, the soil in the spacer section would be compacted and potentially the runoff volumes and rates would increase. Grass that is not maintained has the potential to become patchy and turn to bare ground. The grass under the panel may not get enough sunlight and die. Fig. 1 shows the result of the maintenance trucks frequently driving in the spacer section, which diminished the grass cover.

The effect of the lack of solar farm maintenance on runoff characteristics was modeled by changing the Manning's n to a value of 0.02 for bare ground. In this scenario, the roughness coefficient for the ground under the panels, i.e., the dry section, as well as in the spacer cell was changed from grass covered to bare ground ($n = 0.02$).The effects were nearly identical to that of the gravel. The runoff volume increased by 7% from the grass-covered to the bare-ground condition. The peak discharge increased by 72% when compared with the grass-covered condition. The runoff for the bare-ground condition also resulted in an earlier time to peak by approximately 10 min. Two other conditions were also modeled, showing similar results. In the first scenario, gravel was placed directly under the panel, and healthy grass was placed in the spacer section, which mimics a possible design decision. Under these conditions, the peak discharge increased by 42%, and the volume of runoff increased by 4%, which suggests that storm-water management would be necessary if gravel is placed anywhere.

Fig. 5 shows two solar panels from a solar farm in New Jersey. The bare ground between the panels can cause increased runoff rates and reductions in time of concentration, both of which could necessitate storm-water management. The final condition modeled involved the assumption of healthy grass beneath the panels and bare ground in the spacer section, which would simulate the condition of unmaintained grass resulting from vehicles that drive over the spacer section. Because the spacer section is 53% of the cell, the change in land cover to bare ground would reduce losses and decrease runoff travel times, which would cause runoff to amass as it

Fig. 5. Site showing the initiation of bare ground below the panels, which increases the potential for erosion (photo by John Showler, reprinted with permission)

moves downgradient. With the spacer section as bare ground, the peak discharge increased by 100%, which reflected the increases in volume and decrease in timing. These results illustrate the need for maintenance of the grass below and between the panels.

Design Suggestions

With well-maintained grass underneath the panels, the solar panels themselves do not have much effect on total volumes of the runoff or peak discharge rates. Although the panels are impervious, the rainwater that drains from the panels appears as runoff over the downgradient cells. Some of the runoff infiltrates. If the grass cover of a solar farm is not maintained, it can deteriorate either because of a lack of sunlight or maintenance vehicle traffic. In this case, the runoff characteristics can change significantly with both runoff rates and volumes increasing by significant amounts. In addition, if gravel or pavement is placed underneath the panels, this can also contribute to a significant increase in the hydrologic response.

If bare ground is foreseen to be a problem or gravel is to be placed under the panels to prevent erosion, it is necessary to counteract the excess runoff using some form of storm-water management. A simple practice that can be implemented is a buffer strip (Dabney et al. 2006) at the downgradient end of the solar farm. The buffer strip length must be sufficient to return the runoff characteristics with the panels to those of runoff experienced before the gravel and panels were installed. Alternatively, a detention basin can be installed.

A buffer strip was modeled along with the panels. For approximately every 200 m of panels, or 29 cells, the buffer must be 5 cells long (or 35 m) to reduce the runoff volume to that which occurred before the panels were added. Even if a gravel base is not placed under the panels, the inclusion of a buffer strip may be a good practice when grass maintenance is not a top funding priority. Fig. 6 shows the peak discharge from the graveled surface versus the length of the buffer needed to keep the discharge to prepaneled peak rate.

Water draining from a solar panel can increase the potential for erosion of the spacer section. If the spacer section is bare ground, the high kinetic energy of water draining from the panel can cause soil detachment and transport (Garde and Raju 1977; Beuselinck et al. 2002). The amount and risk of erosion was modeled using the velocity of water coming off a solar panel compared with the velocity and intensity of the rainwater. The velocity of panel runoff was calculated using Manning's equation, and the velocity of falling rainwater was calculated using the following:

$$V_t = 120\, d_r^{0.35} \quad (1)$$

where d_r = diameter of a raindrop, assumed to be 1 mm. The relationship between kinetic energy and rainfall intensity is

$$K_e = 916 + 330 \log_{10} i \quad (2)$$

where i = rainfall intensity (in./h) and K_e = kinetic energy (ft-tons per ac-in. of rain) of rain falling onto the wet section and the panel, as well as the water flowing off of the end of the panel (Wischmeier and Smith 1978). The kinetic energy (Salles et al. 2002) of the rainfall was greater than that coming off the panel, but the area under the panel (i.e., the product of the length, width, and cosine of the panel angle) is greater than the area under the edge of the panel where the water drains from the panel onto the ground. Thus, dividing the kinetic energy by the respective areas gives a more accurate representation of the kinetic energy experienced by the soil. The energy of the water draining from the panel onto the ground can be nearly 10 times greater than the rain itself falling onto the ground area. If the solar panel runoff falls onto an unsealed soil, considerable detachment can result (Motha et al. 2004). Thus, because of the increased kinetic energy, it is possible that the soil is much more prone to erosion with the panels than without. Where panels are installed, methods of erosion control should be included in the design.

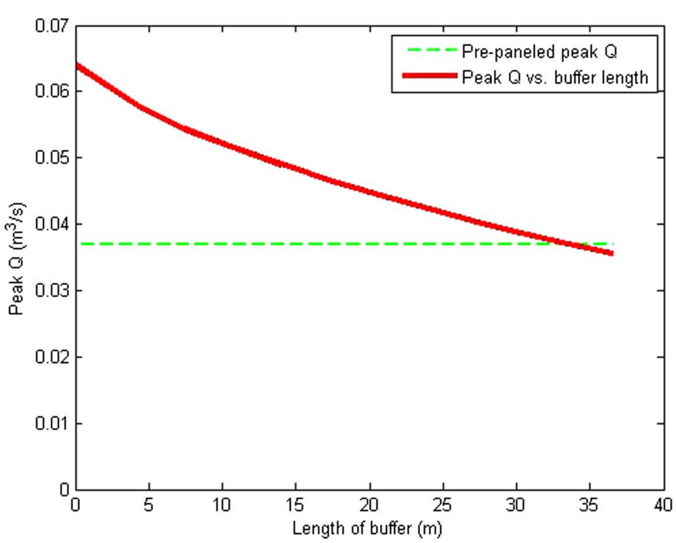

Fig. 6. Peak discharge over gravel compared with buffer length

Conclusions

Solar farms are the energy generators of the future; thus, it is important to determine the environmental and hydrologic effects of these farms, both existing and proposed. A model was created to simulate storm-water runoff over a land surface without panels and then with solar panels added. Various sensitivity analyses were conducted including changing the storm duration and volume, soil type, ground slope, panel angle, and ground cover to determine the effect that each of these factors would have on the volumes and peak discharge rates of the runoff.

The addition of solar panels over a grassy field does not have much of an effect on the volume of runoff, the peak discharge, nor the time to peak. With each analysis, the runoff volume increased slightly but not enough to require storm-water management facilities. However, when the land-cover type was changed under the panels, the hydrologic response changed significantly. When gravel or pavement was placed under the panels, with the spacer section left as patchy grass or bare ground, the volume of the runoff increased significantly and the peak discharge increased by approximately 100%. This was also the result when the entire cell was assumed to be bare ground.

The potential for erosion of the soil at the base of the solar panels was also studied. It was determined that the kinetic energy of the water draining from the solar panel could be as much as 10 times greater than that of rainfall. Thus, because the energy of the water draining from the panels is much higher, it is very possible that soil below the base of the solar panel could erode owing to the concentrated flow of water off the panel, especially if there is bare ground in the spacer section of the cell. If necessary, erosion control methods should be used.

Bare ground beneath the panels and in the spacer section is a realistic possibility (see Figs. 1 and 5). Thus, a good, well-maintained grass cover beneath the panels and in the spacer section is highly recommended. If gravel, pavement, or bare ground is deemed unavoidable below the panels or in the spacer section, it may necessary to add a buffer section to control the excess runoff volume and ensure adequate losses. If these simple measures are taken, solar farms will not have an adverse hydrologic impact from excess runoff or contribute eroded soil particles to receiving streams and waterways.

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