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Modeling Solar Farm Hydrology using EPA SWMM

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ABSTRACT

With the demand for green energy rapidly increasing, solar energy as a renewable energy source is expanding across the world. Implementing solar energy on a large scale requires solar farms installation on land covering hundreds of acres of area. Solar farms also change the existing land use and affect the hydrological response of the catchment. However, the impact of solar farms on catchment hydrology is rarely studied due to the lack of established methods to model and difficulty in modelling their unique land cover. The areas over which solar panels are installed are impervious on the panel and pervious underneath it, making it challenging to model. In this study, a framework is proposed to model the hydrological response of a solar farm using EPA SWMM. The framework split each row of the solar farm into four sections, the impervious solar panel, a wet section that captures the majority of runoff from the panel, a spacer section that encompasses the space between the solar panel rows, and an underpanel section which represents the space under the solar panel. The runoff from one section is routed to the next section in the order of natural water flow. All these sections represent one row of the solar farm, so the runoff from each row is then routed to the next row until the limiting length of sheet flow is reached. Then, all the sheet flow runoff from the solar panel rows is routed to an open channel conduit that represents shallow concentrated flow. This pattern is followed for the rest of the solar farm area, and the conduits are then connected to an outfall. With this general setup, many variables such as the slope of land, slope direction of the solar panels, and rainfall events can be easily modified to understand the effect on hydrology for specific scenarios. In this study, a solar farm in State College, PA is used as a case study to develop the SWMM model. Then, a pre-construction and a post construction solar farm model is developed on SWMM based on the properties of the case study site. Using these models, several simulations were conducted for various design storms to calculate the additional runoff created by the construction of the solar farm. The post construction solar farm model had a higher total runoff volume and a higher max flow than the preconstruction model for all the simulated storm events. The original solar farm SWMM model is then modified to study the hydrology under different solar farm orientations such as varying site slopes and solar panel direction. The framework can serve as an easy tool to study the hydrological response of the catchment before and after the installation of solar farms and to help study runoff and erosion mitigation strategies.

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Chapter 1

Introduction

Solar Farms

The energy sector is a dominant contributor to climate change and accounts for around 60% of total greenhouse gas emissions (UN Department of Economic and Social Affairs., 2018). Moreover, the U.S. Energy Information Administration (EIA) projected a 50% increase in the world’s energy usage by 2050 (Kahan, 2019), so countries around the world are looking to solar energy for a cheaper, cleaner, and renewable source of energy. Solar energy is becoming increasingly cheaper, and the average cost of photovoltaic solar panels has dropped nearly 70% since 2014 (Solar Energy Industries Association (SEIA), 2021). A study conducted by the U.S Department of Energy (2021) suggests that solar energy could account for close to 40% of the nation’s electricity supply by 2035 and 45% by 2050.

Solar energy can be implemented in numerous ways, and one method of implementing solar energy large scale is through Solar Farms. Solar Farms (also referred to as solar parks or solar plants) are large-scale, ground-mounted solar installations that use photovoltaic (PV) panels (Hyder, 2022). Solar panels exist several feet above the ground, and they are mounted to the ground using metal rods. The solar panels can be arranged in different ways, but they are generally organized as sections of solar panel arrays, and the solar panel tile angles may even change throughout the day to have an optimal solar energy capture. The average size of a single solar farm can range from a few acres in residential-scale contexts to thousands of acres for large utility solar farms. Moreover, these solar installations can exist over many different types of land uses including farmland, grassland, bare soil, cropland, lawns, pastures, and even gravel or concrete.

Implementing solar energy at a large scale requires a substantial amount of land, and one concern regarding the expansion of solar farms is loss of agricultural land. However, the ground disturbance caused by the actual mounting of solar panels and other solar farm infrastructure is typically less than 5% of the solar farm land, and only around 25- 40% of the land is over-sailed by the solar panels (Scurlock, 2014). Therefore, many solar farms employ mixed-use land practices, in which the ground beneath and surrounding the solar panels is utilized for purposes such as sheep grazing, plant growth, and farming. Livestock grazing is a popular option for the dual use of solar farms because low intensity grazing in solar farms can be a cost-effective approach to managing grassland while also boosting its conservation value (Scurlock, 2014). The practice of using solar farm land for crop production is referred to as agrovoltaics. One technique of integrating crops into solar farms is through strip-cropping of high-value vegetable or non-food crops under or in between rows of solar arrays. Agrovoltaics has several advantages because the vegetation utilizes runoff from the solar panels, and it provides water quality benefits such as reducing runoff and increasing soil conservation (Scurlock, 2014).

While implementing solar farms has several advantages and may be the key to supplying the energy needs of the future, it is also important to consider the potential negative effects it may have to the environmental. For instance, construction of solar farms could modify the landscape, soil properties, and vegetation. Changes in vegetation and site upkeep can also have an influence on soil carbon dynamics and habitat (Yavari et al, 2022). Moreover, the additional impervious surfaces of the solar panels can impact the hydrology of the site and lead to increased runoff and soil erosion. In the report from U.S. Department of Energy (DOE) (2018) photovoltaic installations are expected to increase to 1,618 GW by 2050, needing around 6.6 million acres of land. Hence, it is critical to explore how these solar farms can be implemented in a sustainable manner considering its effect on hydrology, soil properties, vegetation, and change in landscape. This study explores the effect of solar farm construction on landscape hydrology and stormwater management.

Stormwater Management for Solar Farms

Considering the rapid expansion of solar energy and the amount of land it requires to implement, it is important to consider the impact of large-scale solar farm implementation on stormwater management systems. Stormwater management strategies are commonly used to mitigate the consequences of land-cover changes that result in increased runoff volumes and rates (Cook & McCuen, 2013). Since new solar farms will inevitably change the land use of the existing area, further research is needed to understand how this alteration in land use affects stormwater runoff volume and peak flow rate. Due to the unique site layout of a solar farm, it is difficult to estimate impacts of solar farms on runoff. The solar panels on these sites reside several feet above ground, and while solar panels are impervious, the ground beneath the solar panels are generally pervious. Hence, the solar panel zones cannot be described as merely impervious or pervious, making it complicated to conduct runoff calculations.

For solar farm development, there are currently just a few known stormwater management methods. At least 30 states lack regulations on how to deal with stormwater runoff once a solar farm is built (Yavari et al, 2022). There are ten states that have specific stormwater management guidelines for solar farms, with the guidelines focusing mostly on 'low impact development' approaches. These LID practices aim to mitigate runoff mainly through infiltration and a little through evapotranspiration. The practices are focused on recommending the best soil qualities, vegetation, and land cover for the solar farm's location. For instance, most of the stormwater management guidelines recommend solar farms to be constructed on land with a low slope and well drained soils with low slip potential. Moreover, the guidelines also recommend that soil compactions should also be avoided during construction of the solar field site. Many of these stormwater management recommendations also suggest that a certain interspace width between rows of solar panels be maintained and recommend that at least 80-90% of the ground retains plant cover (Yavari et al, 2022). All these strategies aim to lower overall runoff volume and peak flow from the solar farm site by preventing soil erosion and boosting infiltration.

Solar farms can be organized and arranged in different variations, and solar farm sites can have many different land and soil properties. Hence, it is critical to account for these diverse configurations when modeling solar farm hydrology. Some of the varying configurations explored in this paper are sites slopes and solar panel slope direction. Slope is an important parameter in hydrology because it has a big impact on runoff velocity, infiltration, and soil erosion. Hence, solar farms are generally developed on flat lands with slopes less than 5%. However, there is not sufficient research on the landscape hydrology of solar farms with higher site slopes. Cook and McCuen (2013) conducted a study performing hydrological modelling of solar farms, but the study only looked at scenarios with slopes between 1% and 5%. Other hydrological studies on solar farms have been conducted with site locations mainly in the Midwest where the land is mostly flat. However, Pennsylvania and other northeast regions have a much more sloping and hilly topography. Hence, to develop solar farms in these regions, it is necessary to understand the effect of higher site slopes on solar farm hydrology. Moreover, the slope direction of the solar panels also plays a significant role in the hydrological behaviors of solar farms. A solar farm with panels sloped in the same direction as the site slope will have different infiltration and runoff patterns compared to a site where the panels and site are sloped in opposite directions. There is currently insufficient research comparing the hydrological differences of solar farm sites with various land slope and panel slope configurations.

There are numerous methods that can be utilized to calculate the runoff generated from a given area, but the unique setup of a solar farm complicates modeling the hydrology because a single section of land is both impervious and pervious at the same time. The physical solar array that receives the rainfall is impervious and has no infiltration capacity, but the land right underneath the solar panel that does not receive rainfall is generally pervious and allows for infiltration. Currently there are a few research papers concerning the stormwater modelling of solar farms, but the research still lacks modelling the hydrology of solar farms through a conceptual framework. The modelling approach used in these studies include HEC-HMS and Flow-2D. Research from research from Barnard, Agnaou, and Barbis (2017) uses a one-dimensional approach and only utilizes the curve number method to calculate and route runoff. One limitation of this method is that it calculates curve number based on percent imperviousness of a solar farm section or row, but with this method it is difficult to account for the infiltration occurring on the underpanel sections of a solar farm.

This study proposes to use United States Environmental Protection Agency (US EPA) Storm Water Management Model (SWMM) to model the hydrology of solar farms. The main goal with this project is to compare the changes in runoff before and after development a solar farm, assessing the effect of varying storm events on solar farm hydrology, and analyze changes is hydrology due to varying solar farm configurations. The solar farm along Orchard Rd (behind the Mount Nittany Medical Center), state college, Pennsylvania is chosen as a case study to model in SWMM and assess the runoff pre and post solar farm construction. One of the main reasons this site was chosen was because of its large slope. Like mentioned earlier, the developers generally seek relatively flat land, less than 5% slope, for solar farm installations. However, it is necessary to consider the impact of less ideal landscape conditions such as a high land slope and its effect on runoff. Moreover, there has been relatively little research on the hydrology for solar farms with larger slopes. This study evaluates whether changes in existing land will cause significant changes in runoff volume and peak flow that will require the need for stormwater management practices.

Chapter 2

SWMM Model

Modeling a Single Solar Panel Row

In ground mounted solar systems, the solar panels are mounted above the ground using metal supports. Hence, during a rain event, most of the water hitting the impervious solar panel goes into the spacer section between the solar panel arrays. The section of the space between the panels where the runoff from the solar panel flows into is denoted as the “wet area”. The remaining space excluding the “wet section” between the solar panel arrays is denoted as the “spacer section”. The section underneath the solar panel is denoted as the underpanel, and this section does not receive rainfall directly, but it does receive runoff from the other sections. The runoff from each of the section flows into depends on the solar farm configuration.

One of the solar panel configurations is when the solar panel and the site have the same slope direction. In this instance, the runoff from the solar panel flows into the wet section, and then the excess runoff from the wet section flows into the spacer area, and the excess runoff form the spacer area flows into the underpanel area of the next solar panel row. Figure 1 shows a 2D top view schematic of this configuration, but it does not show the last runoff routing where excess water from the spacer section goes into the underpanel of the next solar farm array. Figure 2 shows a 3D illustration of the water flow between the sections of solar arrays for this configuration.

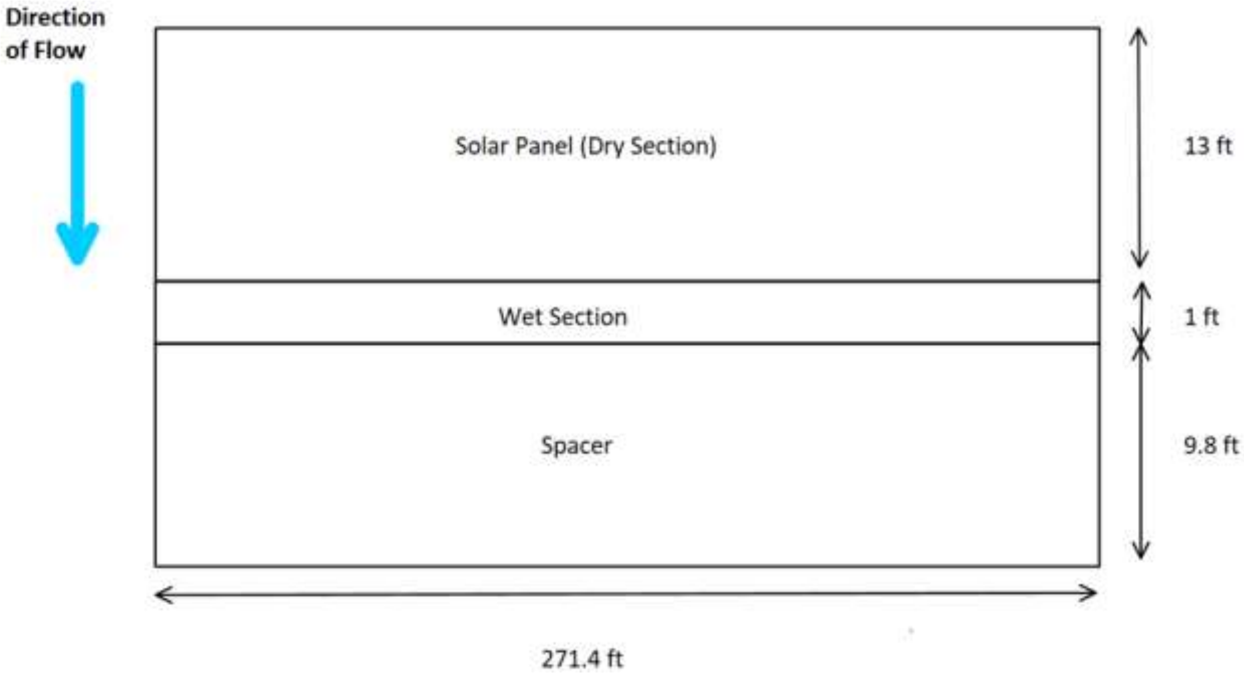


Figure 1: Schematic of a Single Solar Farm Row with Flow Direction with dimensions from the case study solar farm. (Plot is not drawn to scale)

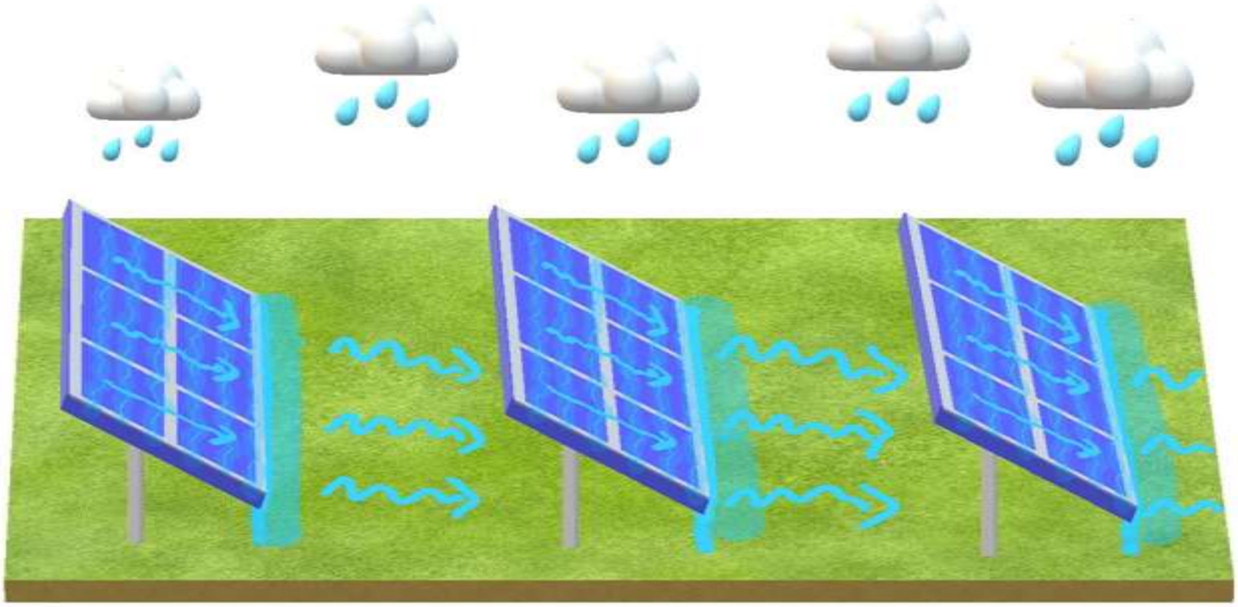


Figure 2: 3D schematic of Solar Panel Rows with the panels and site being slopes in the same direction

This study also explores a different scenario where the solar panel and site slope in varying directions. Hence, in this case, the runoff from the solar panel goes into the wet section, but then the runoff from the wet section flows into the underpanel area of the same solar panel row, and then the runoff from the underpanel goes into the spacer section, and lastly the runoff from the spacer section flows into the wet area of the next solar panel rows. Figure 3 shows a 3D illustration of the water flow of solar farm array for this configuration.

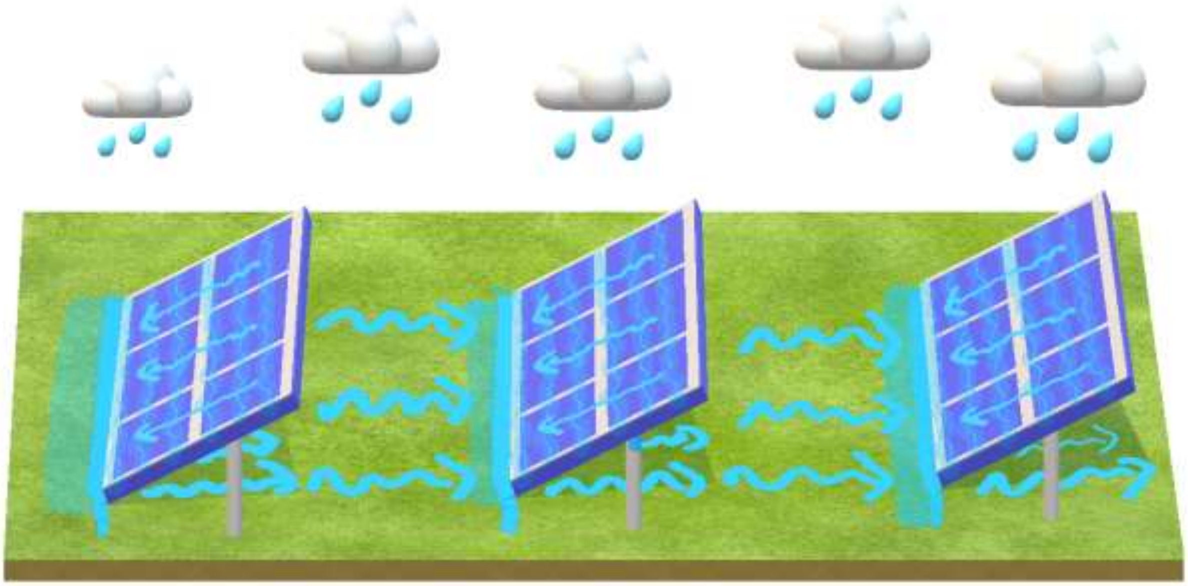


Figure 3: 3D Schematic of Solar farm with opposing site and panel slope directions

To model the solar arrays in SWMM, each row of the solar farm is split into four sections. There is the actual panel section, which is considered impervious, and all the runoff from the solar panel goes to a 12-inch wide “wet section” for both configurations described above. The other connections between the underpanel, wet section, and spacer depend on the solar panel and site set up.

Using the schematic models in Figures 1 and 2, EPA SWMM was used to model the hydrology and runoff. Each of the sections in a single row of the solar farm was modeled as induvial sub-catchments. All the runoff from the solar panel sub-catchment is routed to the wet section sub-catchment. In the configuration where the panels and the site have the same slope, the runoff from the wet section sub-catchment is routed to the spacer sub-catchment. The spacer sub-catchment runoff is routed to the under-panel of the next row of solar panel. In the second row, however, runoff from both the solar panel and the under panel is routed towards the wet section sub-catchment. The same pattern repeats for the following rows. In the configuration where the land has opposing slope directions, the subcatchment runoff routing is slightly different. The solar panel sub-catchment runoff is routed to the wet area sub-catchment, and the wet area runoff is routed to the underpanel subcatchment of the same row. The underpanel runoff is routed to the spacer subcatchment, and then the spacer subcatchment runoff is routed to the wet area subcatchment of the next row.

The solar panel, wet section, and the spacer are all connected to the same rain gage because they all receive direct rainfall. The under-panel sub catchment is connected to a rain gage that had 0 inches of precipitation because the under panel does not receive a significant amount of the rainfall due to the solar panel above it.

This SWMM model set-up for a single solar panel row is then expanded to model the entire solar farm section. First, to obtain dimensions, slopes, and properties of a solar farm, a solar farm study site is chosen for this project. The dimensions and properties of this study site is used to create the initial SWMM model. Later, changes to different properties are made to the SWMM model to simulate different scenarios and gain a better understanding of the hydrology in solar farms.

Study Site Area

The Solar Farm site used to create the initial SWMM model exists behind the Mount Nittany Medical Hospital along Orchard Rd, State College, PA. One of the main reasons for this site selection was its high site slope. Solar farm developers usually look for relatively flat land, so it is helpful to understand the impact on runoff volume and peak flow of solar farms with large site slopes. The section of the solar farm used to create the SWMM model is highlighted in Figure 4 using a yellow box.

Figure 4: Satellite image of Orchard Road, State College PA solar farm site section

The solar panel length, spacer length, site slope, and solar panel width were measured manually using a tape measure. An assumption of 1 foot was made for the width of the wet area. The soil data were obtained from websoilssurvey (https://websoilsurvey.sc.egov.usda.gov/App/WebSoilSurvey.aspx). Table 1shows all the measurements of the study site that was utilized in the SWMM model development. A few assumptions were made about the site while inputting the data into SWMM. The site is modeled to have 10 rows of solar panels, with all the rows being the same size. While this does not exactly match the solar farm site section, it is assumed that the relatively small deviations will not create significant differences in the results.

Table 1: Solar Farm Site measurements used in SWMM Model

Measurement	**Value**
Row Length (ft)	271.4 ft
Underpanel width	12.5 ft
Solar Panel width	13 ft
Site slope	23%
Solar panel Slope	25%
Spacer Section Width	9.8 ft
Hydrological Soil Group	B
Soil Suction Head	7.33 in
Soil Conductivity	0.216 in/hr
Total Area	64593.2 ft

Modeling Entire Solar Farm Section

After modelling one row of solar panel arrays on SWMM, the next step is to create a model for the whole solar farm section. Initially, the thought was to continue the same pattern described in chapter 2.1 for one solar panel row for the rest of the rows in the solar farm

However, the SWMM model set-up for a single solar array assumes sheet flow (overland flow) from one subcatchment to another. Sheet flow or overland flow can be generally described as flow depth approximately less than 0.1 ft (Rossman & Simon, 2022). However, sheet flow has a limiting length, so the runoff may not be sheet flow for the entire solar farm. Chapter 15 from the national engineering handbook on Time of Concentration suggests that the limiting length of sheet flow can be calculated using the equation described below (Kent, 2012):

$$l = \frac{100\sqrt{S}}{n}$$

where:

n = Manning’s roughness coefficient

l = limiting length of flow, ft

S = slope, ft/ft

The ground cover in the solar farm site in Orchard Rd, is assumed to be Bermuda grass, and overland flow manning’s n to be 0.41 for Bermuda Grass (Table 6, Environmental Protection Agency, Rossman, & Simon, 2022). The measured slope of the site was 23% and using these measurements and the equation above, the limiting length was calculated to be 1169 ft. However, the SWMM manual and other sources suggest that the maximum overland flow is generally 100 ft, and since 1169ft is much larger than 100 ft, a maximum sheet flow length of 100 ft is assumed for this study. Since a row of the solar farm (solar panel, wet section, spacer) has a combined width of 23.8 ft, this indicates that the runoff from the solar farm will be sheet flow for about 4 solar panel rows. The sheet flow then becomes shallow concentrated flow, so the solar farm is modeled to have sheet flow for 4 rows. Then, after 4 rows, the runoff is assumed to be shallow concentrated flow. The shallow concentrated flow is modeled as a grass lined, parabolic open channel in SWMM. The runoff from the first 4 row solar panels is connected to a junction that is connected to a conduit representing the shallow concentrated flow. The runoff from the next four rows of the solar panel is connected to another junction, and this junction is connected to a second conduit to represent the shallow concentrated flow. The conduit containing runoff from the first four junctions is connected to the conduit containing runoff from the next four junctions. Same was repeated for the last two solar panel rows. The last conduit is then attached to an outfall. This framework is demonstrated in Figure 5 that shows the SWMM model of the entire solar farm section.

The SWMM user manual suggest that shallow concentrated flow usually has flow depths between 0.1 and 0.5 ft and an average of these numbers, 0.3 ft, is assumed for this model (Rossman & Simon, 2022). The length of the first conduit is assumed to be the width of four solar panels rows, which is 95.2 ft. The SWMM user manual had a separate table of Manning's roughness values for shallow concentrated flow, and the vegetal manning's number of 0.03 is used for this model. The second conduit carrying the runoff from the next four rows to the next junction has a max depth of 0.3 ft and a length of 47.6 ft. This is because the length of the second conduit is the width of the last two solar panel rows. All the conduits are considered parabolic open channel and is assumed to have top width of 1 ft. The junction containing the runoff from the last two rows is then connected to an outfall.

The invert elevations of the junctions are determined using the site slope. Since the site slope is 23% and the length of the first conduit is 95.2 ft, the elevation difference between the first two junctions is 21.9 ft. Similarly, since the length of the second conduit is 47.6 ft and the site slope is assumed to be uniform throughout the solar farm, the elevation difference between the second and third junction is 10.95 ft. After the configuration of the SWMM model for the whole solar farm section with the appropriate parameters, the next step is to run simulations and obtain hydrology data.

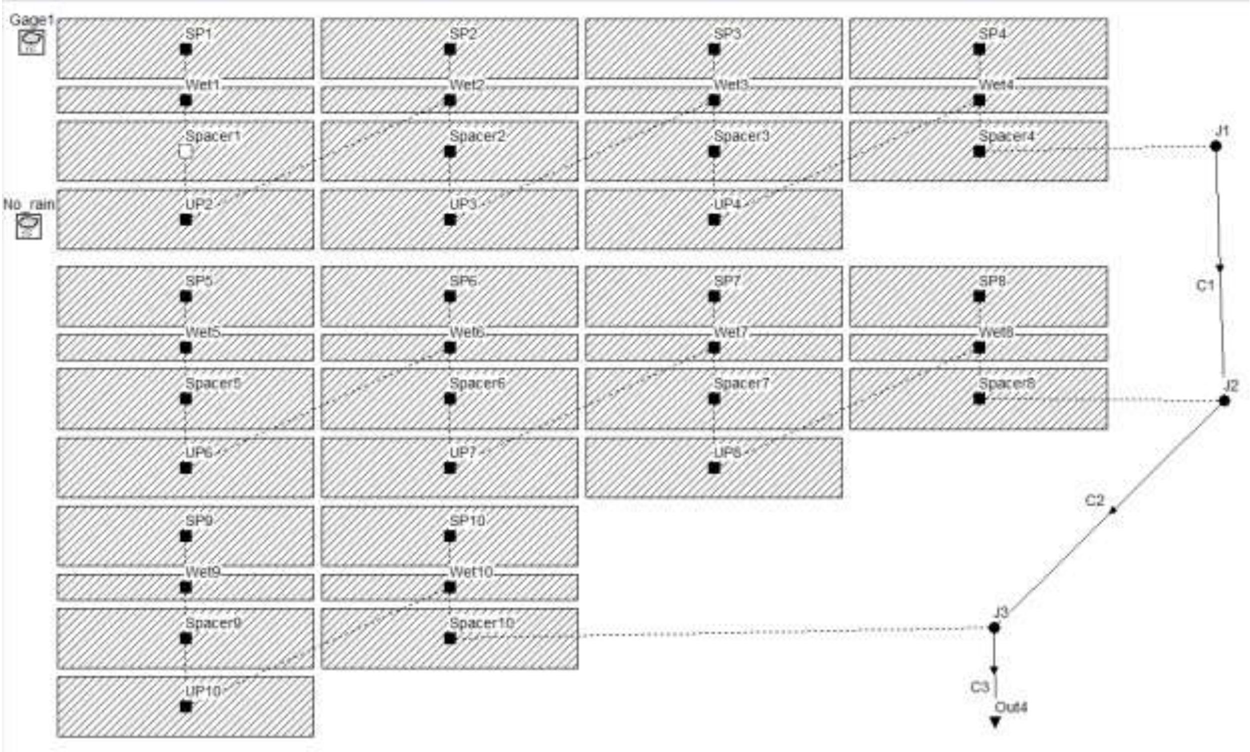


Figure 5: SWMM model set up for solar farm with panel and site slope in the same direction

Experimental Setup

This study aims to understand the change in hydrology post solar farm construction, solar farm runoff during various storm events, and the change in runoff with varying solar farm layouts; this includes varying site slopes and solar panel slope direction.

To understand the effect on runoff volume and peak flow post solar farm construction, and SWMM model was developed to simulate the land before the construction of a solar farm. This simulation was done using the SWMM model and site properties of the Orchard Rd, solar farm site. The pre solar farm SWMM model consisted of one large subcatchment containing the same soil properties, land area, and infiltration data as the solar farm SWMM model. The length of the site was the same as the length of a solar panel row, which is 271.4 ft, and the width of the site was the width of 10 solar arrays, which is 238 ft. The subcatchment also had 0% imperviousness. Table 2 shows all the pre solar farm properties inputted into the SWMM model. The subcatchment is then connected to an outfall, and the Green and Ampt Infiltration method (Rossman & Simon, 2022) is used to estimate the runoff in this model.

Table 2: Pre-Solar Farm site propertied used in SWMM Model

Measurement	**Value**
Area Length (ft)	271.4 ft
Area width	238 ft
Manning’s N for pervious area	0.41
Manning’s N for impervious area	0.01
% Impervious	0%
Suction Head	7.33
Conductivity	0.213
Initial Deficit	0.25

To understand the effect of varying storm event on solar farm hydrology, the type II SCS rainfall distribution was utilized for 6 hour and 24-hour storms. The SWMM model with the properties of the Orchard Rd. study site was utilized for this simulation. NOAA rainfall data for State College, PA area was used to gain the rainfall depths of a 2 yr, 10 yr, 25 yr, 50 yr, and a 100 yr, rainfall (https://hdsc.nws.noaa.gov/hdsc/pfds/).

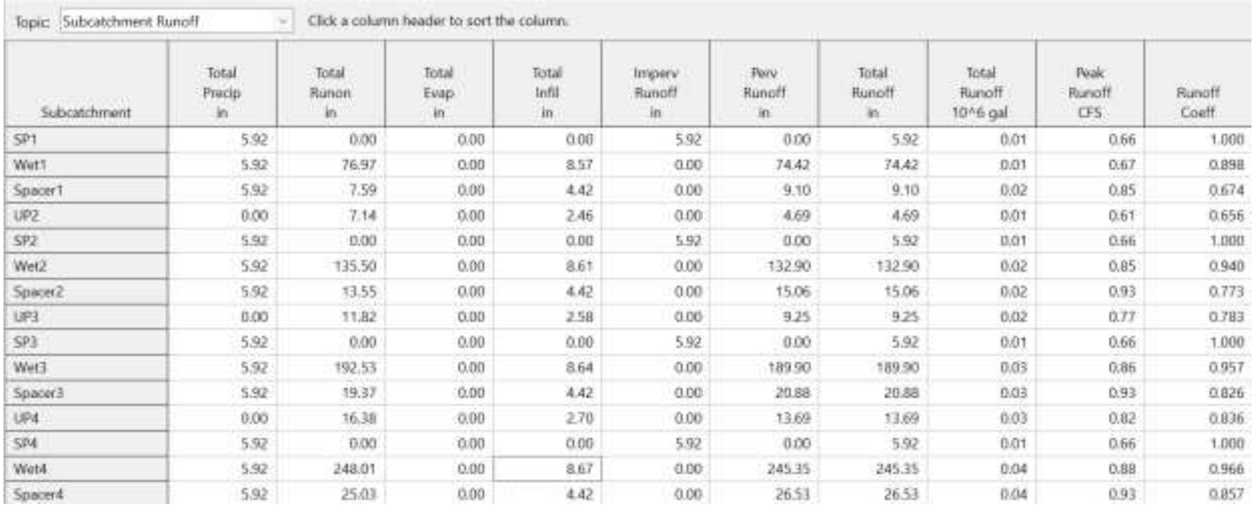
This study also looks to understand the effect on hydrology for varying solar farm configurations. Hence, using the original SWMM model for the Orchard rd. study site solar farm, changes were made to different properties to run simulations on different scenarios. This includes varying site slopes, opposing site and panel slope directions, and varying spacer areas. The site slope of the study site solar farm is 23%, and site slopes of 5%, 10%, 15% and 25% were also simulated. To compare the impact of hydrology in a solar farm where the solar panels and site are sloped in different directions, a simulation is run using a SWMM model set-up shown in Figure 6 and illustrated in Figure 3. It is also important to consider that different solar farms are spaced out and arranged differently, so this study also looks at varying spacer sections widths. The width of spacer section of the study site is 9.8 ft, and widths of 7 ft, 5ft, 12 ft, and 15 ft are also simulated. All solar farms are arranged and set up differently due to varying factors, so it is essential to understand how runoff volume, peak flows, and infiltration changes with different arrangements to help find standardized stormwater management practices.

Chapter 3

Solar Farm Model Simulation Analysis

Case Study Site Simulation

Once the SWMM models are created, a simulation of a 24-hour 100-year storm is run using the original SWMM model based on the Orchard Rd. solar farm site discussed in chapter 3. A 24-hour 100-year storm is chosen as a the design storm for the simulation. This simulation gives insights on infiltration and runoff patterns among the subcatchments areas. Figure 7 shows the summary results table of subcatchment runoff from the first four solar panel rows. This section of the analysis mainly looks at the first four solar panel rows because after four rows, the runoff goes from sheet flow of shallow concentrated flow. Moreover, the same pattern that occurs in the first four solar panel rows repeats for the next four rows, and the last two rows.



Topic: Subcatchment Runoff

Click a column header to sort the column.

Subcatchment	Total Precip in	Total Runon in	Total Evap in	Total Infil in	Imperv Runoff in	Perv Runoff in	Total Runoff in	Total Runoff 10^6 gal	Peak Runoff CFS	Runoff Coeff
SP1	5.92	0.00	0.00	0.00	5.92	0.00	5.92	0.01	0.66	1.000
Wet1	5.92	76.97	0.00	8.57	0.00	74.42	74.42	0.01	0.67	0.898
Spacer1	5.92	7.59	0.00	4.42	0.00	9.10	9.10	0.02	0.85	0.674
UP2	0.00	7.14	0.00	2.46	0.00	4.69	4.69	0.01	0.61	0.656
SP2	5.92	0.00	0.00	0.00	5.92	0.00	5.92	0.01	0.66	1.000
Wet2	5.92	135.50	0.00	8.61	0.00	132.90	132.90	0.02	0.85	0.940
Spacer2	5.92	13.55	0.00	4.42	0.00	15.06	15.06	0.02	0.93	0.773
UP3	0.00	11.82	0.00	2.58	0.00	9.25	9.25	0.02	0.77	0.783
SP3	5.92	0.00	0.00	0.00	5.92	0.00	5.92	0.01	0.66	1.000
Wet3	5.92	192.53	0.00	8.64	0.00	189.90	189.90	0.03	0.86	0.957
Spacer3	5.92	19.37	0.00	4.42	0.00	20.88	20.88	0.03	0.93	0.826
UP4	0.00	16.38	0.00	2.70	0.00	13.69	13.69	0.03	0.82	0.836
SP4	5.92	0.00	0.00	0.00	5.92	0.00	5.92	0.01	0.66	1.000
Wet4	5.92	248.01	0.00	8.67	0.00	245.35	245.35	0.04	0.88	0.966
Spacer4	5.92	25.03	0.00	4.42	0.00	26.53	26.53	0.04	0.93	0.857

Figure 6: Summary Table of Subcatchment Runoff from first four solar panel arrays

Figure 6 indicates that the largest total run-on occurs in the “wet area” subcatchments, and it gets increasingly larger for wet areas in rows further down the slope. This is because the wet area has the smallest area and width compared to all the other subcatchments. Additionally, all the runoff from impervious solar panel subcatchment is also routed to the wet area in addition to the precipitation. This nature of the wet section will likely cause the soil to become quickly saturated, preventing sufficient infiltration throughout the storm event. Due to the wet area receiving so much runon altogether, it may also lead to erosion of the soil. Hence, it could be useful to implement some management practices along the wet section to prevent erosion and encourage infiltration. Some practices that could be tested are infiltration trenches along the wet area, or increased vegetation along the wet area. The runon for all subcatchments seems to be increasing as the number of rows increases. This indicates that not all the precipitation is infiltrating in between rows.

Inspecting the runoff hydrograph of the different subcatchments also provides helpful information about the hydrology between the solar panels. Figure 7 shows a runoff hydrograph of the fourth solar panel row, including the underpanel, solar panel, wet section, and the spacer. The fourth solar panel row was chosen because it is the last row that receives all the sheet flow runoff from the previous rows before the runoff turns into shallow concentrated flow.

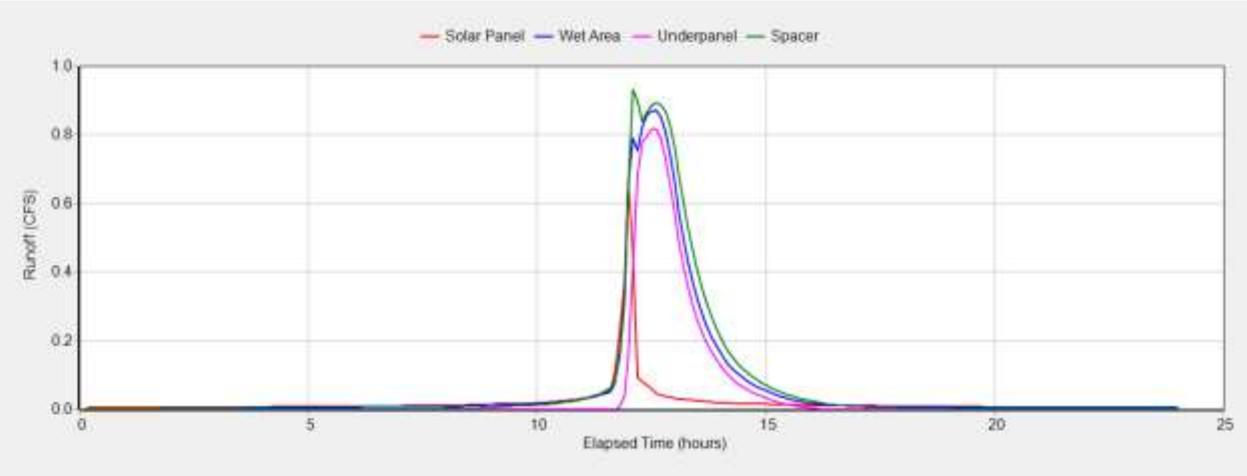


Figure 7: Row 4 Subcatchment Runoff Hydrographs for a 24-hour simulation

The subcatchment hydrographs shown in Figure 7 demonstrate interesting runoff patterns between the solar panel rows. The spacer subcatchment and the wet area have two peaks while the solar panel and the underpanel hydrographs only have one peak, but they are different sizes and occur at slightly different times. The initial peak in the wet area and spacer area is likely caused by a peak flow in the precipitation event because the solar panel hydrograph also experiences this peak at the same time. However, the underpanel does not experience this initial peak because it is not connected to a rain gage, and its peak is caused by the excess runoff from the previous subcatchments. There is a second peak experienced by the wet section, spacer, and the underpanel at the same time, and this peak is likely due to the runoff coming from the other sections because it occurs slightly after the first peak. The spacer section had the largest hydrograph because it receives all the excess runoff from the other subcatchments in the solar panel row.

In addition to understanding the runoff patterns of a solar panel row, it is useful to recognize the infiltration patterns of the subcatchments. Figure 8 shows the infiltrations rates of the solar panel, underpanel, wet area, and spacer subcatchments of row four.

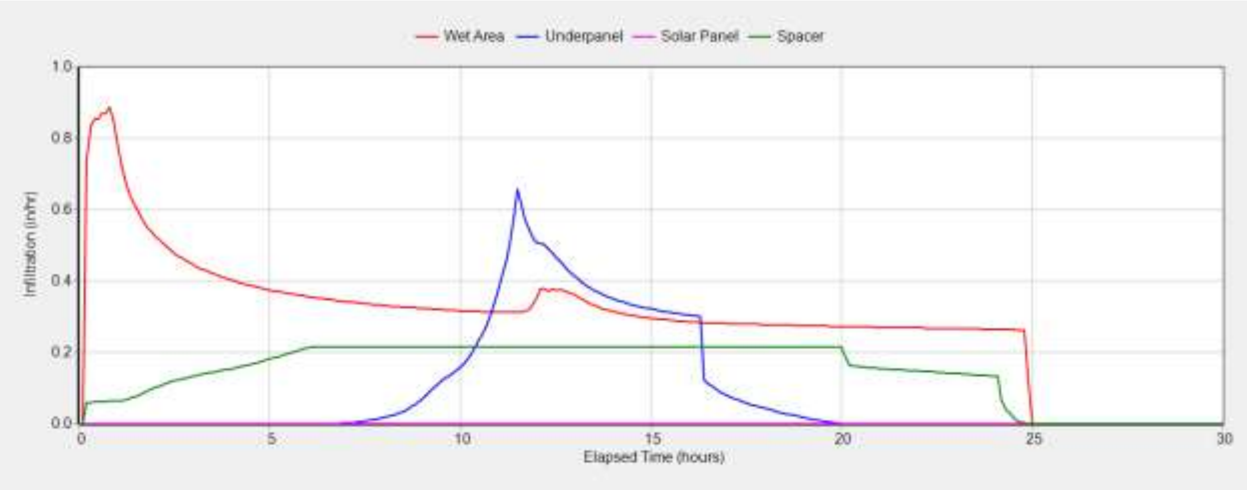


Figure 8: Row 4 Subcatchment Infiltration Rates

The wet section infiltration rate graph generally follows an exponential decay curve where there is an initial infiltration rate, and then the rate slowly decreases until it reaches the steady state infiltration rate. The wet section reaches its peak infiltration rate before all the other subcatchments because it receives both the precipitation from the rain event and all the runoff from the impervious solar panel all at once. The wet section also has the smallest subcatchment area and receives the largest amount of runoff at given time causing the wet section to saturate early. A 0.03inch runoff from 13ft width solar panel is equivalent to 0.39inch runon in the 1ft wide wet section. The solar panel is assumed to be completely impervious, so its infiltration rate is 0 for the whole simulation.

The spacer section follows a similar curve to the precipitation unit the soil becomes saturated. This trend can be seen in Figure 9 which shows the infiltration, runoff, and precipitation rate curves. The infiltration curve seems to flatten out around 10 hours which indicates that the soil is saturated, and the infiltration rate has reached a steady state rate. Runoff is generated when the precipitation rate is higher than the infiltration rate, and this occurs around the peak precipitation rate close to 12 hours; this pattern can be seen in Figure 9.

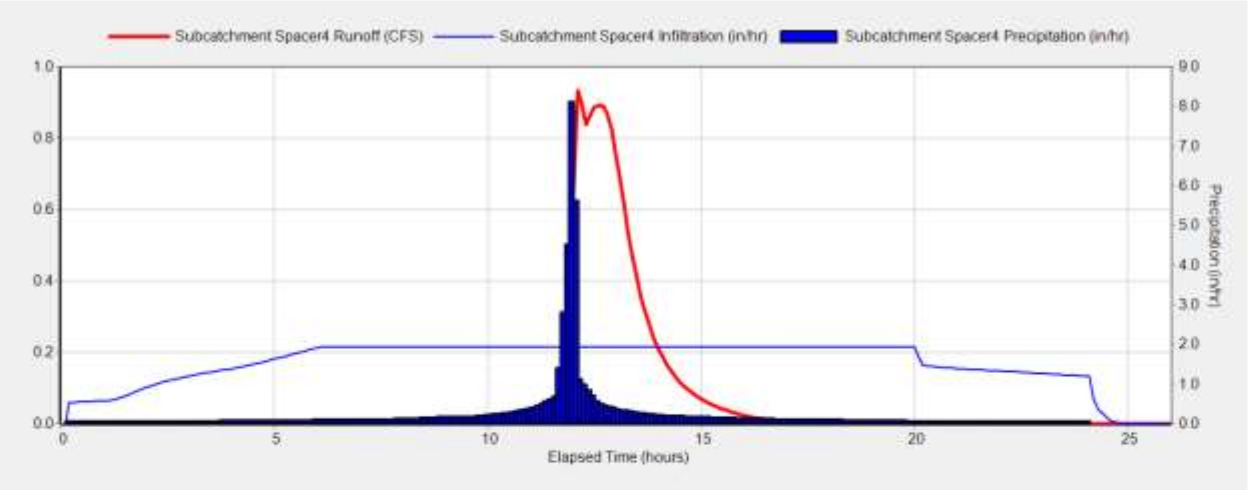


Figure 9: Spacer Subcatchment Runoff, infiltration, and Precipitation rate curves

Lastly, the underpanel infiltration curve loosely follows an exponential decay curve, but it's peak is very delayed. The is likely due to the fact that the underpanel does not receive any precipitation. Hence, it only receives runoff from other subcatchments, and since runoff generates after a precipitation event, the peak infiltration rate for the under panel occurs later in the simulation. Analyzing and understanding the runoff and infiltration patterns of the different subcatchment helps gain a better understanding of the hydrology of a solar farm, and it helps validate that the model is a relatively accurate representation of the runoff and infiltration in an actual solar farm. It should also be noted that the simulations are from an uncalibrated model, SWMM models developed were not calibrated due to lack of measured runoff data.

Pre and Post Solar Farm Development Comparison

One of the main purposes for stormwater management practices is to mitigate the additional runoff that may be caused by new development. Hence, to understand the change in hydrology from the pre solar farm (S.F) construction and post solar farm (S.F) construction, a pre solar farm development SWMM model is created using the same land properties as the existing solar farm, and then both models are run under a 2-year 25-year storm. Then, Runoff Quantity Continuity values from the status report of both simulations were used to compare the hydrology differences in the two model. Table 3 shows the average subcatchment runoff parameter values from both the pre–S. F and post S.F model. It is important to consider that these average values may be misleading because the total area of the pre–S. F model is slightly less than the total area of the post S.F model. This is because the underpanel and the solar panel are modelled as two separate subcatchments. Even though the ground cover area may be the same for both models, the total subcatchment area is larger than the total subcatchment area for the pre–S.F model. Hence, comparing the average values may be slightly misleading because the total subcatchment areas are different.

Table 3: Runoff Quantity Continuity Results for Pre and Post solar farm Models

Parameter	**Pre S.F model**	**Post S.F model**
Total Precipitation Depth (in)	2.640	1.930
Infiltration Loss (in)	1.724	1.473
Surface Runoff (in)	0.919	0.460

Looking at Table 3, the total precipitation value for the pre–S. F model is slightly higher than the total precipitation value for the post S.F model. The 2.640 inches shown for the pre–S. F model comes from the total runoff depth of a 2-year 24-hour storm. The post S.F value had a lower total precipitation depth value even though the model is run under the same 2-year 24-hour storm. This is most likely because the underpanel subcatchment is attached to a rain gage with 0 precipitation, so the total precipitation depth from all the subcatchments is averaged, the value become lower than the total runoff depth of a 2-year 24-hour storm (2.640 inches).

Table 3 indicated that the total infiltration loss depth is higher for the pre–S.F model compared to the post S.F model. It makes sense because even though the amount of area capable of infiltration is around the same for both models, the manner and intensity at which the areas receive the runoff is different. This is largely due to the addition impervious solar panel subcatchments in the post S.F model. In addition to the precipitation from the rain, the wet section also receives all the runoff from the impervious solar panel, which has a much larger area than the wet section. Hence, this high inflow of water into a relatively smaller area leads to reaching the soil capacity much faster, and this could explain the lower infiltration depth in the post S.F model simulation. As mentioned earlier, the difference in areas between the pre S.F and post S.F models could be another reason that the average infiltration depths are slightly different

Table 3 also shows that the surface runoff for the pre–S.F model (0.919 inches) is much higher than the surface runoff for the post S.F model (0.460 inches). This may be due a few reasons. As mentioned in chapter 2.3, the sheet flow runoff from every four rows of solar panels is routed to an open channel to represented shallow concentrated flow because sheet flow generally has a maximum length of 100 ft. Hence, it is likely that the SWMM model does not consider the water directed to the open channel as surface runoff because it is contained within the channel. Even though SWMM may not consider that routed water as runoff, it is meant to represent runoff, leading to a lower average surface runoff value for the post S.F model. Moreover, the lower surface runoff may also be because this is an average value of all the subcatchments combined. Hence, in the post S.F model, the underpanel subcatchments do not receive any rainfall, and this may cause a decrease in the average subcatchment surface runoff value.

Due to the large limitations of comparing the average runoff parameter values, the total outflow volumes and the max flows were then used to better understand the hydrological differences of pre and post construction of a solar farm. In the pre–S.F model, the subcatchment runoff from the entire area is connected to a junction with is then connected to an outfall using a conduit. Similarly, in the post S.F model, the conduits containing the excess sheet flow from the solar panel rows are routed to one junction with is connected to an outfall using a conduit. Hence, looking at the outfall loading will help understand the amount of total runoff coming from the solar farm area before and after the solar farm construction. Simulations for multiple different storm events are run on both the pre and prost S.F models to understand how much additional runoff will be caused by the solar farm. Table 4 shows the outfall volume for pre and post solar farm model from simulating multiple different storm evets.

Generally, with new construction, the goal is that water quantity and water quality must remain the same as pre-developed conditions (Pennsylvania DEP, 2006). While these SWMM models do not help calculate water quality differences, the difference in outfall loading volumes between the two models should be a good indicator of water quantity differences between pre- and post-developed conditions. It is also important to consider the peak flow rate during a storm event and attempt to match the peak flow rate to that of pre-developed conditions. Hence, Table 5 shows the outflow max flows of the pre- and post- developments model for varying storm events.

Table 4: 6-hour and 24-hour storm Pre and Post Solar Farm Construction Outfall Volume

Event Storm	**6 hour**			**24 hour**		
	Pre S.F (10^6 gal)	**Post S.F (10^6 gal)**	**Difference (10^6 gal)**	**Pre S.F (10^6 gal)**	**Post S.F (10^6 gal)**	**Difference (10^6 gal)**
2 yr	0.001	0.013	**0.012**	0.002	0.025	**0.023**
10	0.001	0.033	**0.032**	0.002	0.054	**0.052**
25	0.002	0.049	**0.047**	0.003	0.07	**0.067**
50	0.002	0.060	**0.058**	0.003	0.079	**0.076**
100	0.002	0.068	**0.066**	0.004	0.087	**0.083**

Table 5: 6-hour 24-hour Pre and Post Solar Farm Construction Max Flow

Event Storm	**6-hour Storm**			**24-hour Storm**		
	Pre-S.F (cfs)	**Post S.F (cfs)**	**Difference (cfs)**	**Pre S.F (cfs)**	**Post S.F (cfs)**	**Difference (cfs)**
2 yr.	0.03	0.71	**0.68**	0.03	0.91	**0.88**
10 yr.	0.03	1.28	**1.25**	0.03	1.40	**1.37**
25 yr.	0.03	1.40	**1.37**	0.03	1.40	**1.37**
50 yr.	0.03	1.40	**1.37**	0.03	1.40	**1.37**
100 yr.	0.03	1.40	**1.37**	0.03	1.40	**1.37**

`This study analyzed return period storms of 2-year, 10-year, 50-year, and 100-year storms for a 6-hour and 24-hour time period, and the following storm events are accounted for in Table 4 and Table 5. For the 100-year 24-hour storm event, there is an additional 83,000 gals or 11095.49 cubic ft of runoff after the development of the solar farm. Moreover, the peak flow rate post solar farm development must be reduced by 1.37 cfs for the 100-year 24-hour storm event. Both goals can be achieved through various stormwater infrastructures.

Effect of Site Slopes on Solar Panel Runoff

The ideal land slope condition for a solar farm site is relatively flat (less than 5%) because a high site slope encourages increased runoff velocity and soil erosion. However, some solar farms do exist on sites with higher slopes such as the study site in Orchard rd., so it is important to understand the hydrological behavior of solar farms with higher site slopes. The Orchard rd., site has a site slope of 23%, and slopes of 1%, 5%, 10%, 15%, 20% and 25% are also simulated using SWMM. All other properties except the slope values remained the same among all SWMM models, and a 2-year 24-hour storm is used for all the simulations. Table 6 shows the simulation results from running the SWMM models with various site slopes. The main variables studied are total infiltration loss depth, total surface runoff depth, total outfall loading volume, and max flow in the outfall.

Table 6: Simulation Results for varying Solar Panel Site slopes

	1% slope	**5% Slope**	**10% Slope**	**15% Slope**	**20% Slope**	**23% Slope**	**25% Slope**
Infiltration Loss Depth* (in)	1.652	1.568	1.524	1.498	1.481	1.473	1.468
Surface Runoff Depth (in)*	0.279	0.363	0.408	0.435	0.451	0.460	0.465
Outfall Total Volume (10^6 gal)	0.015	0.020	0.022	0.024	0.025	0.025	0.026
Outfall Max Flow (cfs)	0.37	0.63	0.74	0.82	0.88	0.91	0.93

*****These values are total averages from all the subcatchments, so it is counting additional areas for the solar panel subcatchments. In an actual solar farm, the solar panel sits above the ground, so the panel does not add to the solar farm area. However, these values are still helpful to analyze the hydrology patterns between the site slope variations.

Table 6 indicates that the infiltration loss depth decreases as the slope increases. A higher slope percentage leads to an increase in runoff velocity, which make is difficult for the runoff to infiltrate. A lower infiltration depth will also lead to higher surface runoff, so table 6 also indicates that the surface runoff depth increases as the slope increase. It is also interesting to investigate how much and at what rate the infiltration depth decreases and runoff depth increases as the slope increases. Figure 9 and Figure l0 graphs the infiltration depth and runoff depths over the slope percentages. Figure 9 indicates that the infiltration depth does not decrease linearly as the slope increases. The trendline for the graph follows an exponential decay curve with an equation of y = -0.058ln(x) + 1.6552. There is a larger change in infiltration loss between 0% and 5% slope compared to the infiltration loss change between 20% and 25%. Similarly, the runoff depth also does not increase linearly as the slope increases. Figure 10 demonstrates the change in runoff depth as the site slope increases. The runoff depth increases at a faster rate between the slope is lower, and the runoff depth increases at a much slower rate as the site slope increases.

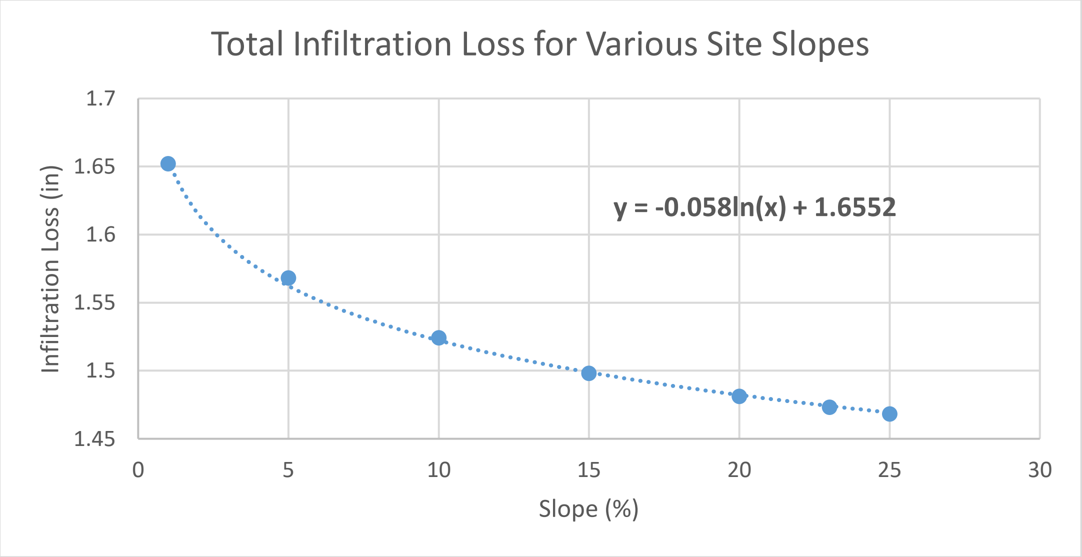


Figure 10: Total Infiltration Loss depth in inches for different site slopes

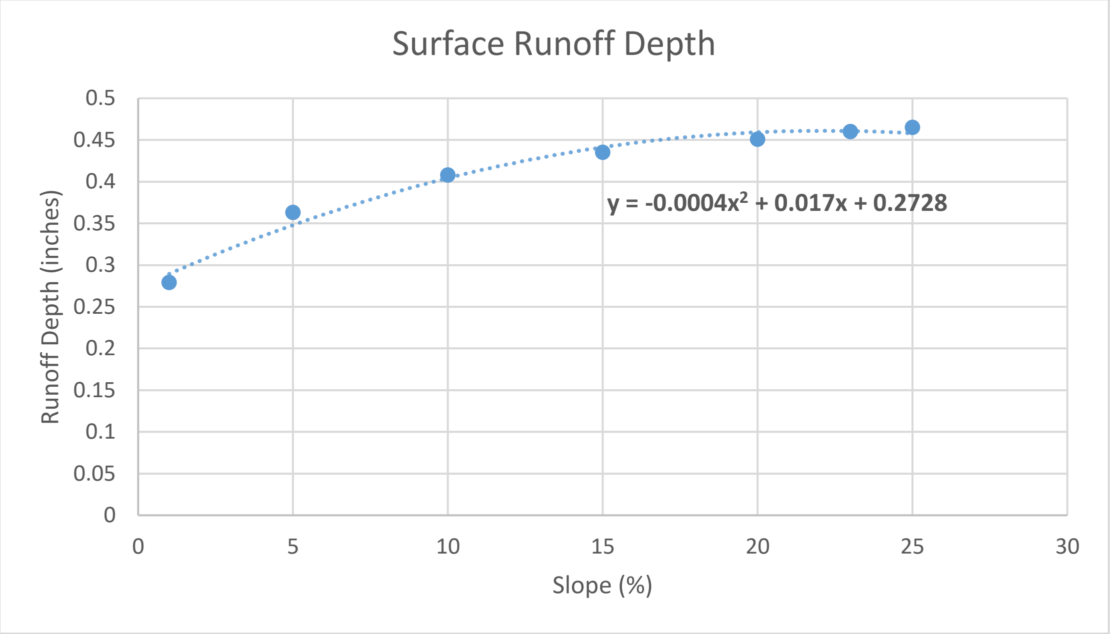


Figure 11: Total Surface Runoff Depth over Various Slopes

In addition to the total runoff depth and infiltration loss depth, the total volume and max flow are at the outfall node are important parameters to inspect; the outfall node is where all the runoff from the site eventually flows into. Table 9 shows that the total volume at the outfall node increases as the slope increases, and this indicates that sites at higher slopes generate more runoff. Table 6 also indicates that the max flow increases as the slope increases, which is expected because a higher slope leads to a faster runoff velocity. It is useful to analyze the inflow rate at the outfall node, and Figure 11 showcases the outfall inflow Hydrograph for varying site slopes. The hydrographs for all the slopes generally have the same shape and peak at the same time, but the peaks occur at different rates. The peak flow is higher for higher slopes, but the peak increases at a slower rate as the slope increases. For instance, the peak flow for the 5% site slope s 36.2% higher than the peak flow at the 1% site slope, but there is only a 5.6% difference in peak flow between the 25% site slope and 20% site sloe. This matches the trend that is exhibited in the total infiltration loss and runoff depth across various slopes shown in Figure 9 and Figure 10. Hence, a lower site slope leads to a smaller runoff volume, smaller peak flow, higher infiltration loss, and a lower surface runoff, but the rate at which these parameters change are not linear as the slope changes.

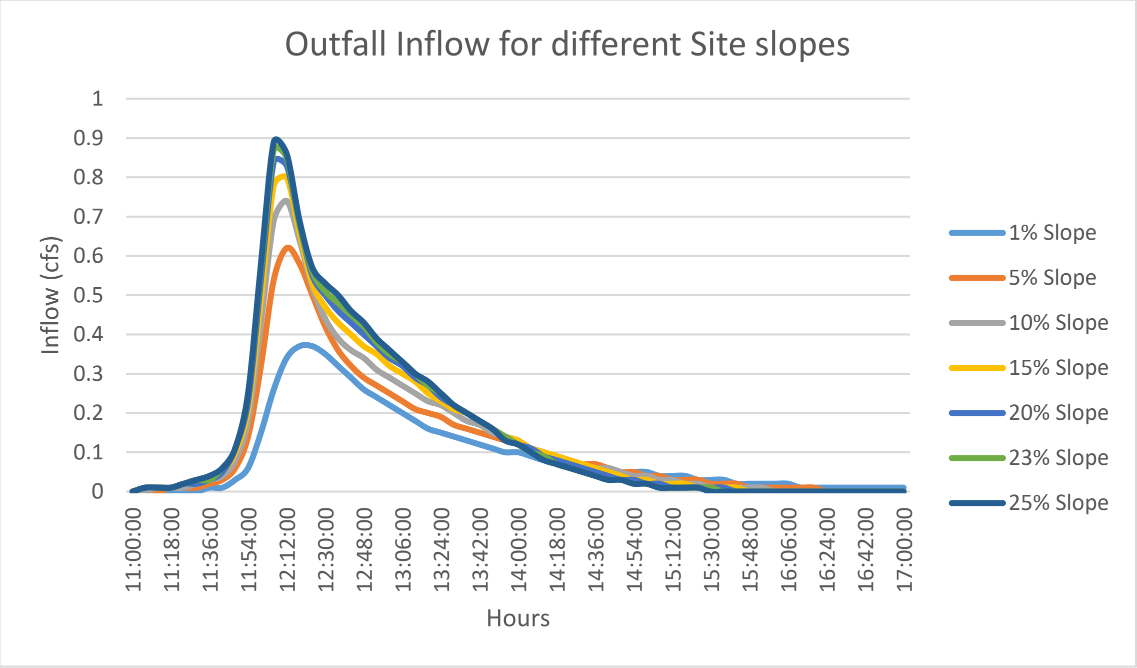


Figure 11: Outfall Inflow Hydrograph for varying site slopes

Solar Farm with Opposing Panel and Site Slope Hydrology Analysis

The solar panels on solar farms can be oriented and sloped in several different ways. Slope direction of a solar panel effects the hydrological response of the solar farm. The solar panels on the study site by Orchard Rd. are sloped in the same direction as the site slope. However, solar panels can also be sloped in the opposite direction of the site slope, so a SWMM model is created to simulate this scenario. Table 7 compares the simulation results between a solar farm model with the opposing panel and site directions (scenario 1) and the Orchard rd. orientation with panel and site sloped in the same direction (scenario 2) for a 24-hour 100-year storm

Table 7: Simulation Results from Scenario 1 and Scenario 2

	Scenario 1	**Scenario 2**
Surface Runoff Depth (in)	0.373	0.460
Outfall Total Volume (10^6 gal)	0.023	0.025
Outfall Max Flow (cfs)	0.5	0.95

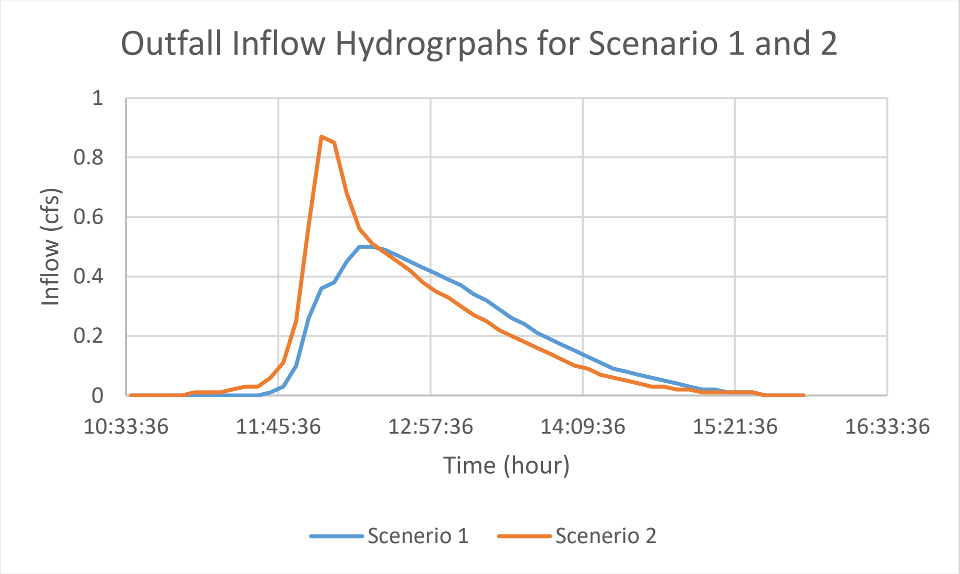


Figure 12: Scenario 1 and 2 Outfall Node Inflow Hydrographs

Table 6 indicates that the total volume of runoff from scenario 1 where the solar panel and site are sloped in opposite direction have a low total runoff volume, a lower max flow rate, and a lower surface runoff depth than scenario 2. A similar trend is also shown in the inflow hydrographs of the outfall nodes from scenarios 1 and 2 show in figure 12. The peak flow for scenario 1 is much lower than the peak inflow rate for on the scenario 2. The hydrographs also have slightly different shapes as the scenario 2 peak flow occurs earlier than the scenario 1 peak flow. These trends can be mainly attributed to the orientation of the solar panels in scenario 1 that allows for the underpanel subcatchments to be fully utilized for infiltration. For every additional impervious area of the solar panel, there is around an equal amount of pervious underpanel that allows for infiltration. In the original scenario where both the panels and the site sloped in the same direction, the underpanels of some of the solar panel rows were not being fully utilized. For instance, the underpanel in the first row of the solar panel is not utilized because runoff from the first solar panel goes directly into the wet section, and the underpanel does not receive any runoff because there aren’t any panels before it. In scenario 1 additional runoff form the wet area goes directly into the underpanel, and since underpanels do not receive any addition precipitation from the rainfall event, it can infiltrate more runoff than the other subcatchments. In scenario 2, however, the runoff from the wet section goes into a spacer section which does receive precipitation from the rainfall event, so it does not infiltrate as much as the underpanel subcatchment because its soil is saturated quickly. This trend can be seen in Figure 14 where the infiltration rate for the underpanel subcatchment is higher than the spacer subcatchment throughout the simulation.

In addition to the difference in total runoff and max flow between scenario 1 and 2, the runoff and infiltration rates within the subcatchment of each solar panel row are also vary between the two scenarios. Figures 13 and 14 show the runoff and infiltration rate curves the subcatchments from the fourth solar panel row for a 24-hour 100-year storm. The fourth solar panel row is last row before the runoff turns into shallow concentrated flow, so its infiltration and runoff patterns are affected by the runoff it receives from the previous solar panel rows in addition to the rainfall event.

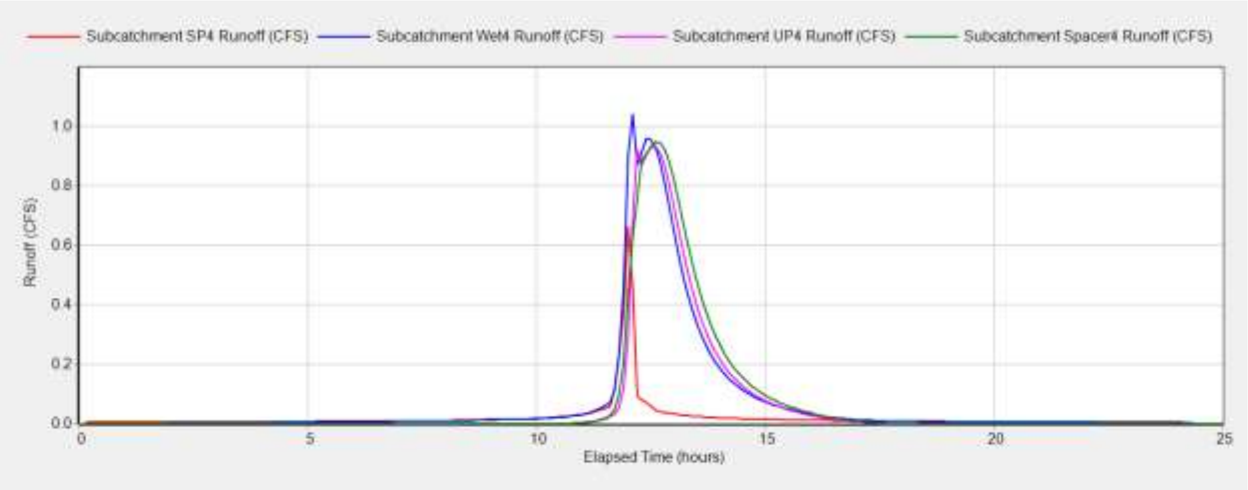


Figure 13: Scenario 2 Row 4 Subcatchment Runoff Hydrographs

The subcatchment hydrographs shown in Figure 13 demonstrates different runoff patterns when compared to subcatchment hydrographs of scenario 2 shown in Figure 7. In scenario 1, the wet subcatchment and the underpanel subcatchment experience two peaks in the hydrographs. The first peak occurs around the same time as the solar panel subcatchment runoff peak, so this indicates that the first peak is caused by all the excess runoff from the impervious solar panel. This is different from scenario 2, where the spacer and wet area had the two peaks in their hydrographs because in that scenario, the wet section is routed to the spacer section. In scenario 1, however, the runoff from the wet section is routed to the underpanel, so the first runoff peak from the solar panel is also experienced by wet area and underpanel subcatchments. While there is a slight increase in the spacer runoff rate while the other subcatchments experiences the first peak, the spacer hydrograph does not experience two peaks. This is largely because the excess solar panel runoff has had enough time and area to infiltrate before reaching the spacer subcatchment. Analyzing and justifying the runoff patterns of each subcatchment helps validate the SWMM model because the different runoff patterns for the different slope orientation match the expected runoff behavior. This study indicates that solar farms where the panels and site slope in opposing direction is a better orientation for reducing runoff volume and peak flow when compared to a solar farm where the panels and site are sloped in the same direction. Hence, when developing a solar farm, it is beneficial to choose a site that allows allow for the solar panels and site to be sloped in opposing directions.

Chapter 4

Limitations

The EPA SWMM modelling software and the model set up had many advantages and allowed for a relatively accurate representation of different solar farm scenarios. There are, however, numerous limitations within this model and assumptions that needed to be made in order to run the simulations. One main limitation with this model set up is that simulations on varying land uses cannot be conducted. This is because the method used to calculate runoff in this study is the Green Ampt method, and the parameters for this method only look at the soil properties and not land use. Initially, the curve number method was utilized to estimate runoff because this method can account for varying land uses. However, when simulations were run under the curve number method, there would be no infiltration on the underpanel subcatchments, which is a crucial component to model a solar farm accurately. Therefore, the Green Ampt method is used for all the simulation because it calcuted infiltration in the underpanel subcatchments.

Another limitation with this model is that numerous assumptions were made about the open channel conduit properties that represented shallow concentrated flow. The conduit measurements were not based on field measurements, so the parabolic shape and the top width of 1 foot were assumptions. Ideally, for futures studies, these parameters would be based on field measurements from an actual solar farm. Similarly, the soil properties such as the suction head and conductivity were obtained through *websoilssurvey*, but the model would have been more accurate if these were calculated using an infiltrometer on the case study site.

Another limitation that exists is when comparing the total precipitation, infiltration rate, and surface runoff rate for the post construction and pre construction of the solar farm. There is an added area in the post construction for solar panel subcatchments that is not included in the pre solar farm construction model. It wouldn’t make sense to add additional area to the pre-construction because that would not be reflective of actual pre-construction area. That would also provide increased infiltration space in the predevelopment model, so the excess runoff volume and max flow would not be an accurate comparison. However, we are unable to avoid the additional area in the post construction period because it is not possible to create a subcatchment of 0 area. While the additional area may affect some of the average values such as the total precipitation, it is not going to significantly affect other values such as total runoff, and peak flow rate because the infiltration area for both pre and post construction models is the same. Even though these limitations prevent the model to perfectly represent the study site, understanding these limitations are a critical step helps draw useful and accurate conclusions from the results. The SWMM models developed in this study were not calibrated due to lack of measured data, and all results from the study should be considered from a relative change perspective.

Chapter 5

Conclusion

With the growing energy demands of the future, United States and countries around the world are looking towards solar as a source of clean renewable energy. Solar Farms are one method of implementing solar energy on a large scale, but solar farms also require a large area of land. Hence, it is crucial to consider the environmental impact of the expansion of solar farms because installation of solar farms can change the land-use, vegetation, and hydrology of the landscape. This study utilized EPA SWMM to develop a hydrological model of a solar farm. A case study area in State College, PA is chosen to create the original SWMM model. Then, parameters such as site slope and panel slope direction were changed to analyze the hydrological response in different solar farm configurations.

The result of this study indicates there is an increase in runoff volume and max flow after the development of the solar farm for all the design storm events that were simulated. Moreover, the SWMM model simulations helped obtained quantitative numbers for the difference in runoff volume and max flow between pre and post development. This data is extremely beneficial when determining what stormwater management practices need to be implemented when constructing a solar farm. In addition to analyzing the hydrological impacts pre and post solar farm development, the SWMM simulations are also run on different solar farm configurations by changing site slope and panel slope direction.

SWMM model simulations are conducted for sites with 1%, 5%, 10%, 15%, 20%, and 25% slopes. The results indicate that that the total runoff volume and max flow rate increases as the site slope increases. It is also important to note that this trend was not linear, and the runoff volume and max flow rate increased at a higher rate when the site slopes were smaller.

This study also compared the hydrological response between solar farms with the same site and panel slope direction and solar farms with opposing site and slope directions. The results indicates that solar farm is opposing site and slope direction has a lower runoff volume and peak flow rate. After conducting the SWMM model simulation on varying solar farm configurations, a solar farm with a small site slope and opposing panel and site slope directions is the ideal configuration to obtain a smaller runoff volume and peak flow rate. The framework developed in this study can be used to investigate the hydrological response of the watershed before and after solar farms are installed, and it can be modified to represent the properties of any solar farm site.

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- **EDUCATION**

The Pennsylvania State University | Schreyer Honors College University Park, PA
- *College of Engineering* | B.S in Biological Engineering (Natural Resource Management)
- Minor in Environmental Engineering
- Certificate in Humanitarian Engineering and Social Entrepreneurship (HESE)

- **PROFESSIONAL EXPERIENCE**

Engineering Sales Intern- Nalco Water June- August 2021 Downingtown, PA
- Provided power plants with water treatment solutions that will reduce water, energy, costs and improve overall safety
- Engaged in problem solving by performing system analysis, conducting water quality analysis, serviced sensors to ensure operations are performing at optimal levels at Exelon Nuclear Power Plant
- Collaborated with 9 account managers to find customer solutions through digital tools for 36 accounts with flat revenue resulting in $500,000 dollars of potential revenue to Nalco

Farm Energy Analyst- Graves Extension Fund October 2020-May 2021 University Park, PA
- Utilized excel to create and publish a 2 user-friendly web-based tools for farmers to identify areas of improvement by analyzing their energy records and farm data.
- Published a Utility Bill analysis fact sheet decoding electric and heating utility bills to assist farmers identify energy and cost saving opportunities.
- Presented Utility Bill analysis information in partnership with Pennsylvania Department of Environmental Protection for a Farm Energy Webinar in front of 40+ farmers.

HESE Program TA -Penn State University August- December 2020 University Park, PA
- Instructed undergraduate students in developing 6 self-sustainable social ventures dedicated to launch in East Africa.
- Assisted in product design and business model creation through data driven evidence-based research
- Led a campus outreach effort by conducting seminars and collaborating with faculty and students from various disciplines to expand the HESE program.
- Published a study in Global Humanitarian Technology conference depicting the positive externalities of social entrepreneurship programs on students entering the workforce

Production Engineering Intern - Fujirebio Diagnostics, Inc May-August 2020 Malvern, PA
- Supported the production activities of the COVID-19 antibody test kits (SARS-CoV-2 IgG) by operating and validating filling and labeling equipment that produced 8000+ testing kits per day.
- Facilitated Root Cause Analysis (RCA) on a case of 2000+ defective labels.

Quality Assurance Intern- Fujirebio Diagnostics, Inc June-August 2019 Malvern, PA
- Administered Batch Record (BR) and Standard Operating Procedure (SOP) document revisions in accordance with Good Manufacturing Practice (GMP).

- Collaborated with various departments to organize and revise Quality Assurance documents

PROJECT AND RESEARCH EXPERIENCE

Greensense February 2020-Present HESE Program

- Collaborated with a multidisciplinary team of 6 students to develop aa social venture dedicated to increasing the efficiency of small-holder farming in Kenya using smart sensing and IoT technology.
- Contacted over 30 Kenyan farmers in order to gather key information for the Front-End Engineering and Design (FEED) study.

Capstone Design- Reading Stormwater Management August

- Collaborated with a team of four to design green infrastructure BMPs that will minimize the flooding of the Spring Street Subway in Reading, Pennsylvania.
- Conducted engineering analysis on potential designs to determine the most cost efficient and effective solution.

ON CAMPUS INVOLVEMENT

Phi Sigma Pi Honors Fraternity 2021-Present

Service Chair | Recruitment Chair

Club Tennis Travel Team 2018-2021

Travel Team Co-Captain (2019-2020)

SKILLS AND AWARDS

The President’s Freshman Award (2019); Proficient in ArcGIS, Hydrology Studio, MATLAB, SolidWorks, Microsoft Office; Languages (English, Hindi, Malayalam)