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Estimating Agricultural Irrigation Water Usage in Delaware, USA

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Irrigation is an important agricultural management practice and the second largest consumer of freshwater resources in Delaware. As more farmland is converted to irrigated agriculture, it is crucial that water resource managers be able to determine reasonable estimates of irrigation water usage in order to protect the resource. This study used a soil water balance approach to simulate irrigation for corn and soybeans in Delaware (USA). The simulations were divided into four scenarios to determine which irrigation management method best represents agricultural irrigation water usage in Delaware. Two scenarios utilized an evapotranspiration-based (ET-based) approach using meteorological data from the Delaware Environmental Observing System (DEOS) with a soil water availability threshold to determine when and how much to irrigate. A second set of scenarios used a calendar-based approach and a rain gauge trigger to simulate irrigation. Analyses were performed to examine the seasonal and spatial variability of irrigation in Delaware and to compare simulated irrigation data to reported water use data provided by the Delaware Department of Natural Resources and Environmental Control's Water Allocation Permit program. Seasonal irrigation varied due to environmental as well as irrigation decision making factors. Spatially, irrigation varied primarily as a result of the soil water holding properties. The ET-based scenario with a fixed amount of irrigation had the best agreement with the reported irrigated water use data. This study demonstrated the utility of high-resolution, environmental data with a soil water balance approach to improve estimates of irrigated water usage at the state and regional scale.

KEYWORDS: irrigation water usage; Delaware; soil water balance model; mesonet

1. Introduction

Monitoring and allocating the use of limited water resources is crucial to the sustainability of human, agricultural, and ecological systems. To manage these resources, accurate estimates of consumption are necessary in every sector and jurisdiction, especially with the increasing impact of climate change. Globally, agriculture is the largest user of water resources, consuming 72% of freshwater resources (FAO, 2021). In Delaware (USA), agricultural irrigation is the second largest consumer of freshwater resources, behind only industrial uses, with an estimated 427,751 m^3 withdrawn per day in 2015 (Dieter, et al., 2018). Irrigation is becoming increasingly vital to the annual success of field crops in Delaware and the Mid-Atlantic region of the United States. Between 2012 and 2017, irrigated cropland in Delaware increased by 22% (~146 km^2) to comprise 37.5% of Delaware's harvested cropland (USDA NASS, 2018). In addition, irrigated agriculture is expected to continue growing in Delaware and throughout the Mid-Atlantic region due to climate change effects on seasonal moisture deficits (McDonald and Girvetz, 2013). Thus, as irrigated farmland expands and climate change leads to greater uncertainty in water resources, it is likely that consumption of freshwater resources by agricultural irrigation will increase significantly in the years ahead, placing even greater demand on a crucial resource.

Like other state environmental agencies around the United States, the Delaware Department of Natural Resources and Environmental Control (DNREC) monitors and regulates agricultural irrigation water use in the state of Delaware. Irrigated water usage data is collected from agricultural users by DNREC and used to make future water allocations. The data are also reported to federal officials with the United States Geological Survey (USGS). However, many agricultural wells in Delaware lack water allocation permits, which prevents accurate estimates of groundwater use by agricultural wells for irrigation and requires many assumptions by DNREC in its annual calculations. This uncertainty is based on a number of factors, including the number of actual irrigation wells in use each year, the area of cropland being irrigated, and the water needs of crops grown on irrigated cropland, among other things. This study will demonstrate a more accurate method for estimating withdrawals from agricultural wells in Delaware in order to better account for and estimate Delaware's irrigation water usage.

Growing season rainfall for agronomic crops (e.g., corn, soybean, etc.) in Delaware can be highly variable from year to year, with a statewide average growing season (April-September) rainfall of 596 mm and a range of 364 mm to 915 mm over the reference period of 1981-2010 (Vose et al., 2014). This variability in rainfall can lead to periodic soil moisture deficits in agricultural fields, which subsequently affects the amount of irrigation required to meet annual yield goals. In many states, water resources are allocated to users based on a number of factors, including availability and demand for the resource. However, Delaware uses a statute to allocate water resources for agricultural irrigation. To ensure adequate water is available for crops, Delaware agricultural irrigation users are provided with an irrigation water allocation based on 7 Del. Code Ann. §§ 60-6010, which states that a water allocation permit for farmland irrigation "shall allow the permittee to utilize up to 20 acre-inches per year, with no more than 10 acre-inches per month". This process for allocating water resources by statute is very imprecise and does not take into account local variability in soil properties or aquifer conditions. Given this uncertainty and potential to improperly allocate water resources, it is necessary to determine a more accurate method to estimate irrigation water usage in Delaware. Improving estimates of irrigation water usage in Delaware ensures water resources are available for all sectors under all weather and climate conditions.

Previous studies have utilized a variety of input datasets and models at various spatial and temporal resolutions to estimate agricultural irrigation water use. Döll and Siebert (2002) used the WaterGAP model and a global raster dataset of irrigated farmland at 0.5° by 0.5° resolution to estimate the optimal water usage by a variety of common crop types and found good agreement with state level water use estimates from the 1995 USGS water use survey of the United States. Wriedt et al. (2009) used the EPIC model to estimate irrigation water usage for Europe, and estimated that the amount of irrigated water needed is between 1.3 and 2.5 times greater than the actual amount of water required by the crops due to limits on water transport efficiency (e.g., canals) and irrigation management practices. More recently, Bhowmik et al. (2020) examined trends in the spatial and temporal variability of reported water use in the United States using irrigation survey data from the USGS. Their study found that irrigation water usage in the eastern United States has increased between 1985 and 2015 because of the expansion (in area) of irrigated agriculture as a response to a warming climate. The increasing trend in irrigated agriculture in the eastern United States was also the subject of a 2013 USGS study, which evaluated two irrigation water usage models to quantify the amount of irrigation being used at the field scale in Georgia and Rhode Island (Levin and Zariello, 2013). That study compared model predictions of irrigation water usage to metered irrigation system data and found reasonably good agreement between predictions from a crop water demand model and flowmeter data in Georgia for crops commonly grown in Delaware, such as corn and soybean. In 2015, the Delaware Geological Survey (DGS) used KanSched2, a crop water demand modeling tool which uses the soil-water balance (SWB) modeling approach described in Allen et al. (1998), to estimate irrigation water usage in southern Delaware (Rogers and Alam, 2008). Their study estimated that between 68.1 million m^3 and 124.9 million m^3 of agricultural irrigation water was used annually on 415.1 km^2 of irrigated farmland in that region between 2005 and 2008, depending on whether it was a wet or dry growing season, respectively (DGS, "Aquifers and Groundwater Withdrawals, Kent and Sussex Counties, Delaware", unpublished report for DNREC, Division of Water, 2015.). Their study modeled agricultural irrigation water usage at the field level, but used Thiessen polygons to represent weather and soil conditions at each irrigated farm field location. This approach resulted in very generalized weather and soil conditions being used as inputs in their SWB model, which limited their ability to compare field estimated irrigation water usage to reported water usage data.

This study improves upon previous irrigation water usage studies performed in Delaware and the surrounding region by modeling field-level irrigation water usage using local irrigation management practices with higher resolution weather and land use datasets. While some of the datasets utilized in this study are unique to Delaware, there is potential for comparable datasets to be developed in other states to perform similar irrigation water usage studies, particularly in the Mid-Atlantic region of the United States, where climate, soil properties, and irrigation management practices are similar. This is particularly the case with meteorological data from the Delaware Environmental Observing System (DEOS) – a statewide mesoscale network (mesonet) of weather stations that is comparable to other mesonets whose data are used for irrigation water management, such as the Oklahoma Mesonet and Kansas Mesonet (Klockow, et al., 2010; Patrignani, et al., 2020).

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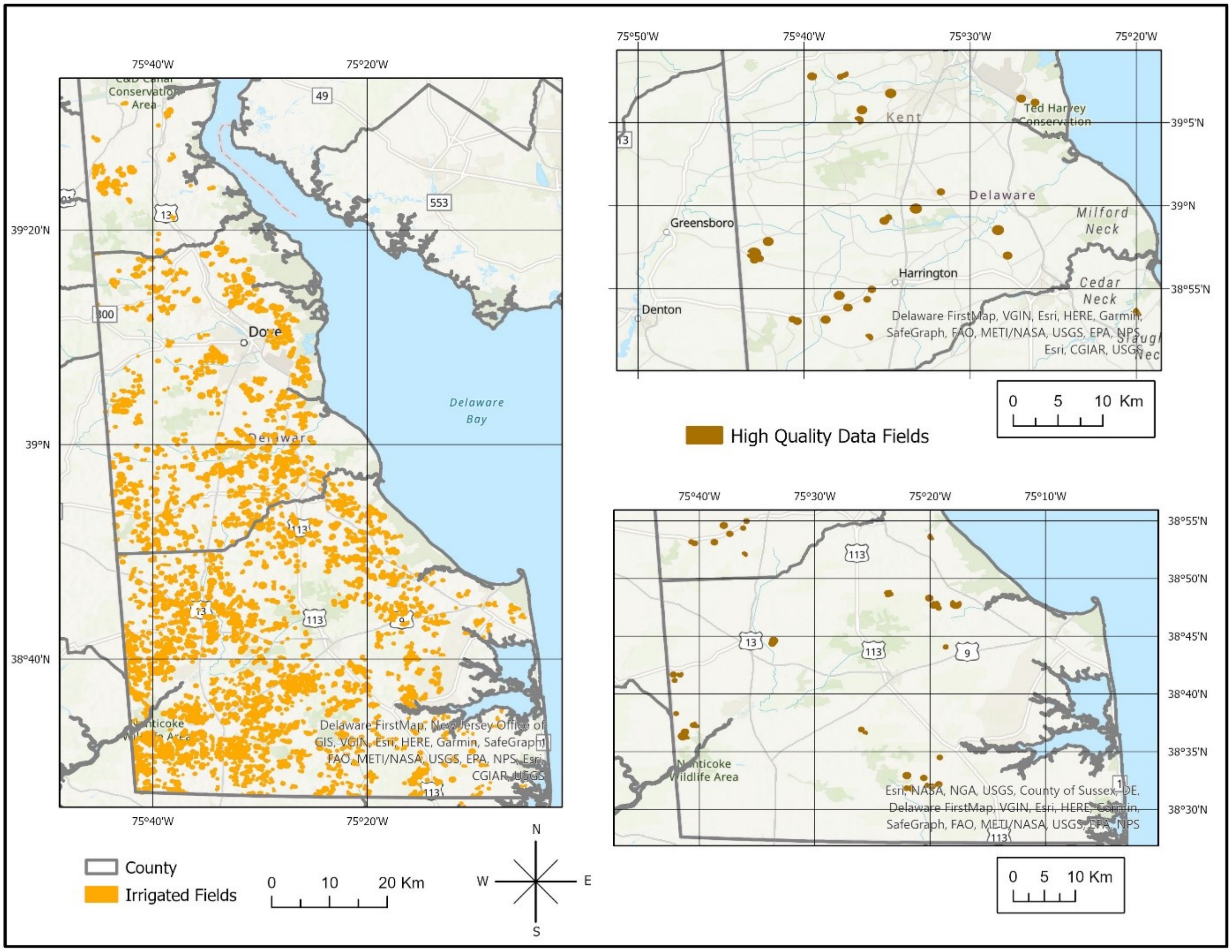

FIGURE 1: Location of all irrigated fields simulated in this study (left) and high quality reported water use data fields in Kent County (top right) and Sussex County (bottom right), Delaware, USA used in comparison against simulated irrigation data.

Several plausible irrigation management scenarios will be used to model irrigation water use in order to determine which management practice best fits field-level reported water use data. Ultimately, the outcomes from this study will allow decision makers in Delaware to better estimate irrigation water usage, thus improving water resource allocation practices in the future, and protecting this valuable resource under potential changes in climate.

2. Materials and Methods

2.1 Data and Model Description

This study developed a crop water demand model using the SWB modeling approach described in the Food and Agriculture Organization (FAO) of the United Nations' Irrigation and Drainage Paper Number 56 (Allen et al, 1998, hereafter FAO56). This model was used to calculate soil water availability, crop water demand, and irrigation water usage for irrigated corn and soybean fields in Delaware from 2010 through 2019. The FAO56 method has been used to calculate irrigation water requirements in many regions around the world (Katerji and Gianfranco, 2014; Cid et al., 2018; Thorp et al., 2017) and requires field-specific crop, soil, and weather data to estimate crop water requirements for a location. This study calculated daily, monthly, and seasonal crop water demand and irrigation water usage for discrete fields identified as irrigated farmland in a spatial dataset produced by the University of Delaware's Cooperative Extension using aerial imagery from 2011 and 2018 (Figure 1). Seasonal, field-specific crop type information, including full season and short season (i.e., fields where corn or soybean are planted after a winter crop, typically wheat or barley, are harvested) crop varieties, was obtained from the United States Department of Agriculture's (USDA) Cropland Data Layer (CDL) dataset by selecting the crop type from the CDL pixel that was co-located with the centroid of each irrigated field (USDA, 2019). Crop emergence date is another important factor in the FAO56 method, as it determines the timing of various stages of growth, rooting depth, and subsequently crop water demand. The USDA NASS produces Weekly Crop Progress and Conditions Reports for Delaware and Maryland which provide weekly estimates of the percentage of farm fields that have reached emergence. For this study, the emergence date for each full season crop was defined as the date of the Weekly Crop Progress and Conditions Report when at least 50% of each crop had emerged, while short season fields' emergence dates for each growing season were set to 30 days after the full season crop emergence date. Soil information is also required by the SWB model in order to estimate soil water availability. Typical soil types in irrigated areas of Delaware are sandy loam and loamy sand soils in the southern part of the state and silt loam soils across the central and northern portions of the state. The relatively low water holding capacity nature of the soils combined with high interannual variability in summer precipitation is a primary reason for the high density of irrigated farm fields in the southern part of the state. Available water capacity (AWC) for each irrigated field was determined by selecting the USDA Soil Survey Geographic Database (SSURGO) soil type that was coincident with the centroid of each irrigated farm field. AWC for the upper 0.6 m of each field was computed as the difference between field capacity (soil water tension of 0.33 bar) and permanent wilting point (soil water tension of 15 bar), as defined in the SSURGO dataset (USDA NRCS, 2020). While corn and soybeans can have full season rooting depths up to ~1.8 meters, this study only modeled soil water availability in the upper 0.6 meters, as this is the common practice for most irrigation applications used in the region.

Two weather parameters are required by the FAO56 method: reference evapotranspiration (ET_o) and precipitation. Daily weather data from DEOS, which has a very dense network of weather stations throughout Delaware (approximately one station every 120 km^2), were used to calculate ET_o and precipitation (Leathers et al., 2020). ET_o is calculated daily at each DEOS station using the FAO Penman-Monteith method for a grass reference surface also described in Allen et al. (1998). ET_o was used to estimate daily crop evapotranspiration for each irrigated field using crop coefficients (K_c) and K_c growth curves from Allen et al. (1998) for corn and soybeans. Daily precipitation data were derived from 5-minute rainfall totals measured by tipping bucket rain gauges at DEOS stations. Daily totals for both parameters were interpolated to each irrigated field location from DEOS stations using a modified Shepard's method (1968), where the range factor was 16.1 km in order to only allow nearby stations to influence the SWB modeled weather conditions for each field.

Simulated water usage results were compared to reported water usage data from a select group of irrigated farm fields designated as high-quality data by the DNREC Water Allocation Branch. This monthly resolution dataset was compiled from annual irrigation water usage records provided by participants (i.e., farmers) in the Delaware Water Allocation Permit Program. The initial comparison dataset resulted in 445 unique farm field growing seasons from 14 different participants in the DNREC Water Allocation Permit program between 2010 and 2019. Additional quality control was performed on the high-quality reported water usage dataset to remove fields not growing corn or soybeans, as well as some duplicate entries. The final reported water usage dataset used for comparison consisted of 259 unique farm field growing seasons across 54 farm fields (see Figure 1) over the 10-year study period. While computation of field-level, irrigation water usage varies from participant to participant, by and large most program participants multiply their irrigation system run

TABLE 1 Description of irrigation scenarios simulated in this study. Note that SWA represents soil water availability and MAD represents management allowable depletion.

Scenario	Description	Trigger to Irrigate	Irrigation Amount
1a	ET-based approach with constant irriga-	SWA < MAD of 50%	10.16 mm per application
1b	ET-based approach with varying irriga-	SWA < MAD of 50%	Only enough irrigation to bring SWA to 50%
2a	Basic calendar-based approach	Prescribed by calendar	10.16 mm per application
2b	Calendar-based approach with Rain Gauge	Prescribed by calendar	10.16 mm per application or skip if rainfall 2 days prior is ≥ 10.16 mm

hours by the flow rate of their system. This method has its limitations, though, since most irrigation systems' flow rate changes over time as the system ages and well condition degrades. Despite these limitations, the DNREC reported water use dataset was used to validate the model predictions, since it is the only known, field-level irrigated water use dataset available for Delaware.

2.2 Irrigation Scenario Descriptions

According to the USDA NASS' Irrigation and Water Management Survey (2018), crop condition and soil feel are the primary methods Delaware farmers use to determine when to irrigate, with soil moisture sensors a distance third. However, crop condition and soil feel methods are not easy to replicate computationally, as they depend heavily on human experience. Soil moisture sensing can be approximated using models, such as the SWB approach used in this paper. Thus, this study uses two other irrigation scheduling methods, an evapotranspiration (ET)-based approach and a calendar-based approach, to see if there was a computationally feasible approach that could reasonably estimate irrigation water usage for Delaware.

Model irrigation was simulated using a scenario-driven approach, whereby irrigation is applied using different scenarios of the ET-based and calendar-based approaches (Table 1). The ET-based irrigation scheduling approach replaces the soil moisture that is removed from the soil by evapotranspiration through irrigation events, but only when the soil moisture has decreased to the point where the crop could become stressed and affect yield. For this study, the ET-based approaches scheduled daily irrigation events based on each field's soil water availability (SWA) relative to an irrigation threshold or trigger. SWA is defined as the relative amount of water available in the root zone of the crop, where 100% equals the field capacity of the soil and 0% represents the permanent wilting point of the soil. The irrigation trigger was defined as 100% minus the management-allowable depletion (MAD), which is the amount of water (represented as a percentage relative to field capacity) that can be removed from the soil before the crop becomes stressed and yield is reduced. For example, if a farmer sets an irrigated field's MAD to 40%, then the farmer will irrigate anytime the SWA drops below 60%, or 100% minus the MAD. It is important to note that some fields have extremely low AWC values, such that the irrigation amounts prescribed in the model scenarios is greater than the AWC of the soil. For these fields, the irrigation application amounts were capped at the AWC value for the field, since it is assumed a farmer would not intentionally irrigate beyond the point of saturation.

Two variations of the ET-based approach were simulated for this study. The first variation, Scenario 1a, used a MAD of 50% to trigger irrigation and simulated a constant irrigation rate of 10.16 mm during each daily irrigation event. The second ET-based variation, Scenario 1b, again used a MAD of 50% to trigger irrigation, but the amount of irrigation applied each time was equal to the amount of irrigation needed to bring the SWA up to 50%. It is important to note that the decision to use a MAD of 50% and an irrigation amount of 10.16 mm in this study were based on an examination of user farm fields' defined in the Delaware Irrigation Management System (DIMS), which is an online irrigation scheduling application developed for Delaware by the Center for Environmental Monitoring and Analysis (CEMA) at the University of Delaware. Both values were the most common MAD and irrigation amount used in the DIMS across all managed fields since it launched in 2012.

For the calendar-based scenarios, 2a and 2b, 10.16 mm of irrigation or no irrigation was applied each day of the growing season based on a crop-specific, weekly irrigation schedule (Figure 2) that is meant to mimic the crop coefficient curves from Allen et al. (1998). Daily irrigation ap-

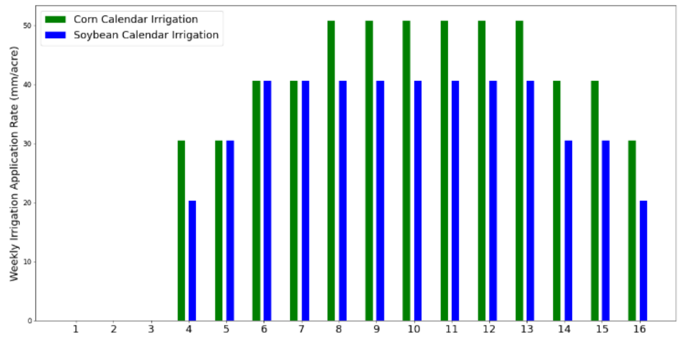

FIGURE 2: Weekly irrigation schedules for corn and soybean for the calendar-based irrigation scenarios (2a and 2b).

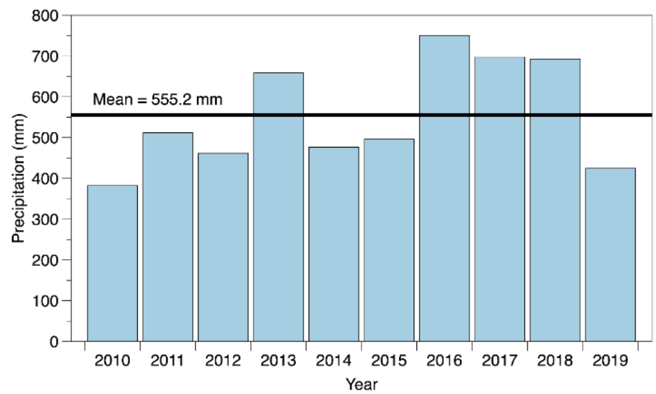

FIGURE 3: Seasonal precipitation for the corn and soybean growing season in Delaware (May through September) for the study period (2010-2019).

plications were evenly distributed throughout each week of the calendar-based irrigation schedule and equaled the total irrigation amount prescribed in the weekly irrigation schedule. While no definitive resource exists that defines daily or weekly irrigation amounts in Delaware, this schedule provides a plausible scenario to represent a farmer's intuition about crop water demand throughout the growing season and generally matches the process described in Hill and Allen (1996). The total amount of irrigation prescribed in each crop type's growing season calendar was 559 mm (22 in) and 457 mm (18 in) for corn and soybean, respectively, based on expert advice about Delmarva agricultural production from University of Delaware Cooperative Extension (J. Adkins, personal communication, January 24, 2020). While Scenario 2a applied irrigation regardless of a field's weather or soil moisture conditions, Scenario 2b skipped a calendar-based irrigation application if the total amount of rainfall in the two days prior to an irrigation application is equal to or greater than the prescribed irrigation amount (i.e., 10.16 mm). Thus, Scenario 2b can be thought of as approximating the behavior of a farmer with intuition about the typical growing season moisture requirements of a crop (i.e., a calendar) while leveraging a simple tool, such as a rain gauge, to limit the number of unnecessary irrigation applications.

3. Results

3.1 Model Sensitivity

Before irrigation was simulated for the full study period, a sensitivity analysis of the FAO56 model was performed by simulating the 2015 growing season for all fields with altered properties of soil water holding capacity, crop type, and emergence date. After each altered field property was simulated for the growing season, the difference in irrigation was quantified relative to the simulation of the 2015growing season with unaltered field properties. Soil water holding capacity sensitivity was examined by altering the soil type for all irrigated farm fields to a high and low soil water holding capacity soil. Higher soil water holding capacity soils (silt/clay) required 31.4% less irrigation, while lower soil water holding capacity soils (sandy loam) required 42.4% more irrigation than the USDA SSURGO soil types assigned to each field. The same type of analysis was performed for crop type, where all irrigated fields were assigned only corn, only soybean, or the USDA Cropscape value for each growing season. This sensitivity test showed that when all fields were planted with soybeans, they required approximately 10.8% less irrigation, while only corn used 21.9% more irrigation. The model's sensitivity to emergence date was also examined by altering the irrigated fields' emergence date to be 2 weeks earlier or 2 weeks later than the predetermined emergence date for each growing season. This analysis showed that the irrigated fields required 6.1% less irrigation for 2 weeks earlier, while 2 weeks later required 6.8% more irrigation. Thus, the FAO56 model is more sensitive to soil water holding capacity, followed by crop type, and less sensitive to emergence date.

3.2 Seasonal Variability

Before comparing simulated irrigation estimates to reported irrigation, an analysis was performed to explore the seasonality of irrigation in Delaware relative to precipitation. Figure 3 shows the growing season (May through September) precipitation for Delaware for the period of record. There is substantial interannual variability in the growing season precipitation ranging from 382 mm during the 2010 growing season to 750 mm in 2016. Care must be taken in interpreting the growing season precipitation amounts. For example, 2016, the year with the largest growing season precipitation, was quite dry until September when nearly 30% of the seasonal precipitation fell, by which time most irrigation use had ceased.

While all ten years were simulated for this study, only the seasonal variability of irrigation from two years are considered in this section; the highest simulated irrigation season (2010) and the lowest (2017). During 2010, irrigation scenarios 1a and 1b (ET-based scenarios) resulted in simulated irrigation estimates of approximately 134.5 million m^3 for the season for the entire state (Figure 4). This large irrigation use was associated with relatively dry conditions from June until the end of August, which is the primary irrigation season for corn and soybeans in Delaware. In comparison, the 2017 growing season saw many substantial summer rainfall events, resulting in approximately one-half the irrigation use at 64.3 million m^3 statewide (Figure 5). Note that scenario 2a (basic calendar scenario) is approximately the same between these two years with a simulated irrigation usage in excess of 265 million m^3 for all fields statewide. Scenario 2b (rain-based calendar method) shows more change between the two years, with a value of 208.1 million m^3 in 2010, and 162.4 million m^3 in 2017 statewide (Figures 4 and 5).

While soil conditions and the ratio of crop types (e.g., corn versus soybean) are virtually the same throughout the study period, environmental conditions (evapotranspiration and precipitation) change from one year to the next statewide. Model estimates of water used by irrigation during this 10-year period ranged from approximately 58 million m^3 (2017) to 134 million m^3 (2010) for scenarios 1a and 1b, while the calendar-based scenarios (2a and 2b) demonstrated a range of approximately 162 million m^3

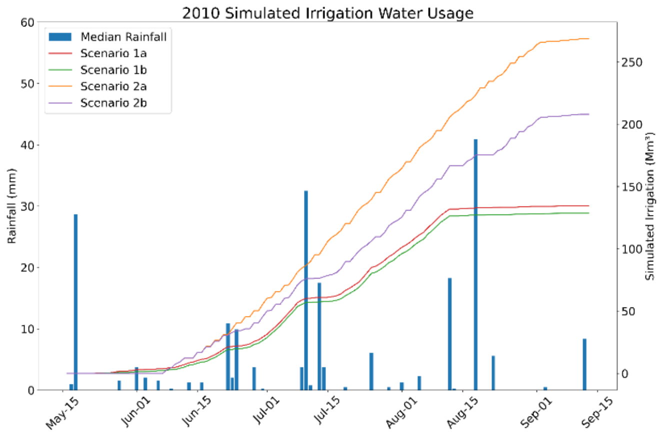

FIGURE 4: 2010 statewide cumulative simulated irrigation for all four scenarios and median statewide daily rainfall.

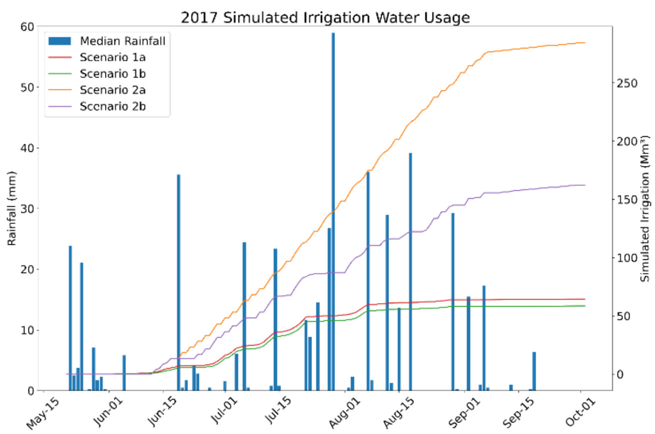

FIGURE 5: 2017 statewide cumulative simulated irrigation for all four scenarios and median statewide daily rainfall.

(2017) to 289 million m^3 (2018). Therefore, it is clear that irrigation management strategies and environmental conditions, particularly the timing of precipitation relative to peak water demand by the crop, synergistically interact to determine irrigation water use. These two factors, working in concert, can lead to drastically different irrigation water use outcomes, impacting water resources in diverse ways.

3.3 Spatial Variability

Two irrigation scenarios (1a and 2b) were chosen to examine the spatial variability of mean seasonal irrigation using all years from the 10-year study period. Figure 6 shows substantial differences in mean seasonal irrigation throughout the study region under an ET-based scenario. Mean seasonal irrigation amounts between 100 mm and 200 mm were seen throughout most fields in Delaware using ET-based methods to simulate irrigation decisions. However, there are some portions of the state with considerably larger values of mean seasonal irrigation. Fields in the south-central portion of the state irrigated as much as 250 mm and fields in the east central portion of the state irrigated as little as 50 mm on average during each growing season using this method to simulate irrigation. The spatial variability of irrigation from the ET-based scenarios is primarily explained by the soil water holding capacities of the fields, which is also consistent with the sensitivity analysis discussed earlier. The lower water holding capacity soils limit the amount of water that can be stored in the soil and made available to the crop, thus more frequent irrigation is necessary to ensure an adequate amount of water is available. Meanwhile, higher water holding capacity soils maintain adequate water availability for crops for longer periods of time, thus reducing the need for more frequent irrigation or rain events. Mean seasonal irrigation is nearly uniform statewide for scenario 2b (Figure 7), with most areas receiving between 300 and 500 mm of irrigation on average. Irrigated fields received significantly higher seasonal irrigation amounts under the calendar-based scenarios relative to the ET-based scenarios. In addition, soil moisture conditions are not a factor in the calendar-based scenarios since irrigation is applied regardless of the amount of soil water available to the crop. Only a few scattered fields in southern Delaware show relatively low irrigation amounts for scenario 2b. This was primarily due to limitations in those fields' soil water holding capacity, which decreased the amount of irrigation per application (i.e., some fields had water holding capacities less than 10.16 mm for the entire managed root zone), and crop types, which tended to be short season soybean fields that require less seasonal irrigation on average than corn and full growing season crops.

3.4 Irrigation Water Usage Comparison

Table 2 shows the mean simulated water usage and standard deviations for all four irrigation scenarios and the DNREC reported water usage data in cubic meters per growing season for all 259 growing seasons used for comparison in this study. Note that scenario 1a and 1b's means are very close to the mean of the reported water usage data, with scenario 1a and 1b differing by only 9.3% and 14.9%, respectively, while scenarios 2a and 2b's means were 2 to 3 times larger than the reported water usage mean. Figure 8a shows a scatterplot comparing simulated water usage for scenario 1a and reported water usage for all comparison fields. This scenario tends to under predict water usage in general, particularly for corn fields, with an R^2 of 0.39. Figure 8b shows a very similar relationship between simulated and reported water usage for scenario 1b with a slightly lower R^2 value of 0.34. Meanwhile, for the calendar-based methods 2a and 2b (Figure 8c and 8d), the relati-

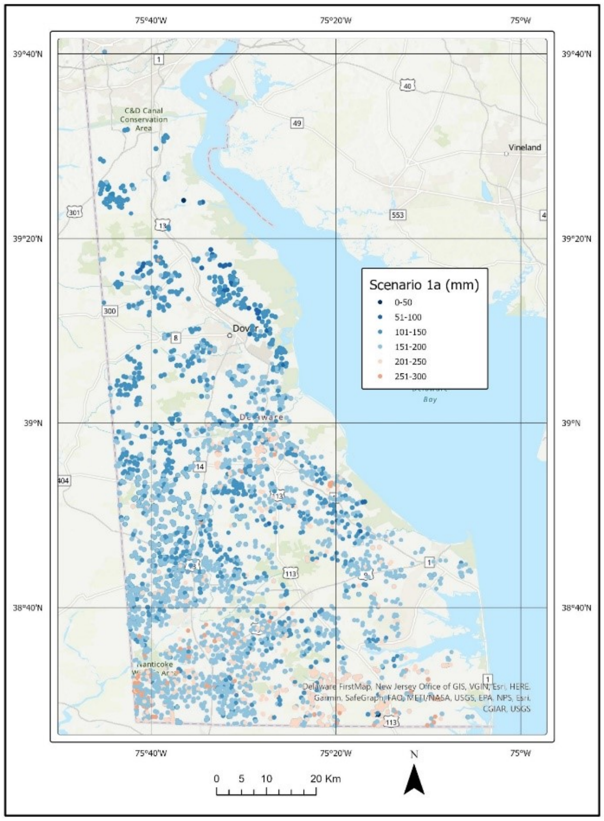

FIGURE 6: Mean seasonal irrigation (2010-2019) for Scenario 1a in millimeters. This scenario is an ET-based method that triggers a fixed amount of irrigation each time a field's soil water availability drops below a threshold.

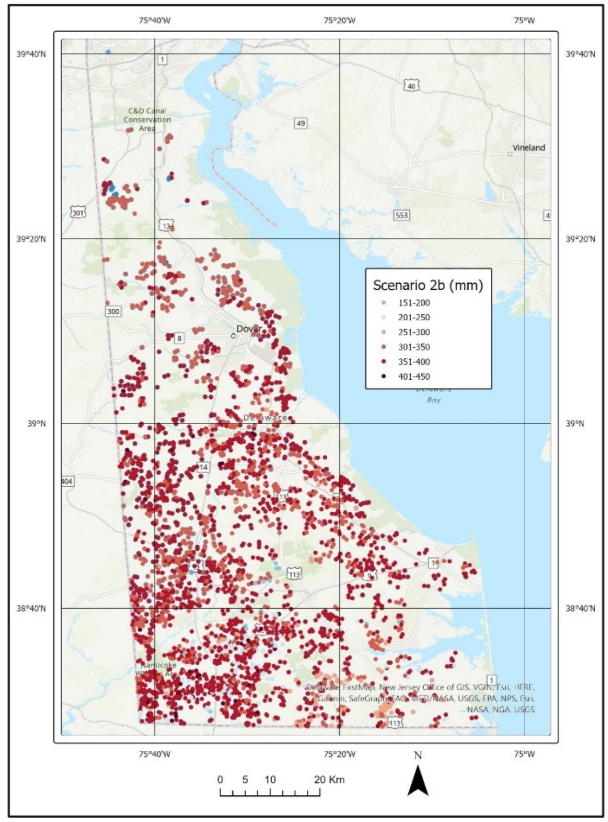

FIGURE 7: Mean seasonal irrigation (2010-2019) for Scenario 2b in millimeters. This scenario is a calendar-based scenario where a fixed amount of irrigation is applied based on a predefined daily irrigation calendar, except when sufficient rainfall has occurred to justify skipping an application.

onship is heavily biased towards over predicting the amount of irrigation applied, particularly with larger farm fields.

One of the main objectives of this study was to model the irrigation decision making process in such a way as to capture the nature and range of irrigation currently taking place in Delaware. Thus, the ideal metric for assessing agreement between simulated water usage and reported water usage should not only account for variance in the data, but bias as well. Table 3 shows model statistics for the comparison analysis, including mean absolute error (MAE), mean bias error (MBE), Pearson's correlation coefficient (r), and the concordance correlation coefficient (r_c), as defined in Lin (1989). The Pearson correlation coefficients, r, for the calendar-based scenarios (2a and 2b) are slightly higher than for the ET-based scenarios (1a and 1b), however, the concordance correlation coefficient, r_c, shows better agreement and lower MBEs for the ET-based scenarios. Figure 7 confirms the ET-based simulations better fit the reported water use data, as the ET-based simulations are far less biased around the 1:1 line than the calendar-based simulations, which tend to over predict irrigation amounts. Finally, scenario 1a shows slightly better agreement and lower error values (MAE and MBE) than scenario 1b. Thus, an irrigation simulation model where a fixed irrigation amount is applied when an irrigation threshold has been surpassed (scenario 1a) performed the best of the four models considered for simulating irrigation water usage for corn and soybean fields in Delaware. Given the minimal requirements of the ET-based irrigation scenario, it's likely that comparable results would be possible in other areas of the globe with similar climate, soil conditions, and irrigation practices using similar types of data.

Crop ET can be very different between soybean and corn due to physiological (i.e., leaf area) differences. This difference in ET rates subsequently affects each crop types' irrigated water demand. Figure 9a-b shows relatively good agreement for smaller corn fields in the ET-based scenarios, while larger corn fields' water usage tends to be under-

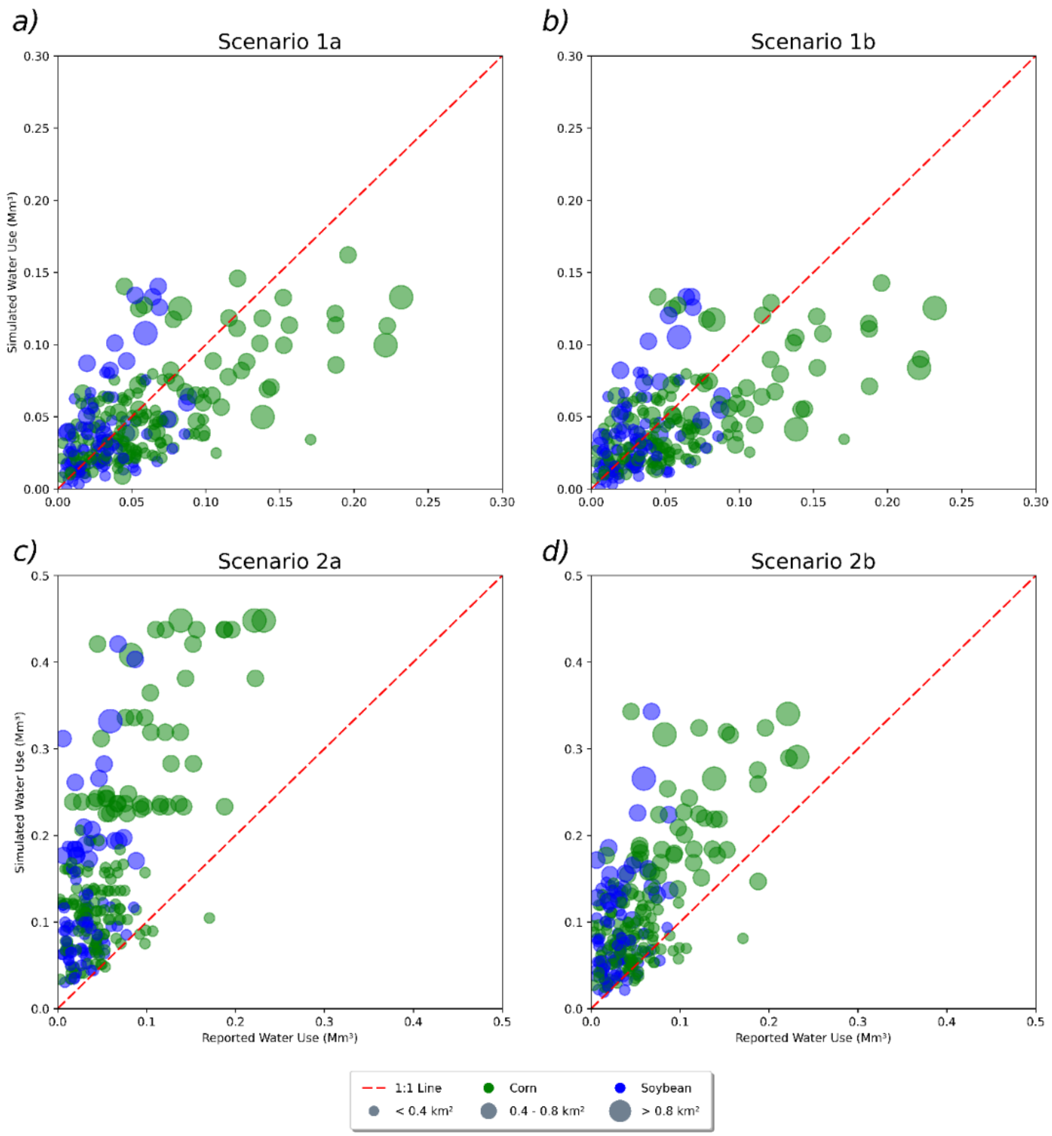

FIGURE 8: Scatterplots of simulated versus reported water usage for scenario 1a (a), scenario 1b (b), scenario 2a (c), and scenario 2b (d). Green circles represent corn fields. Blue circles represent soybean fields. Circle size is related to field size, with larger circles representing larger fields. The red dashed line represented the "ideal fit" of the distribution.

TABLE 2: Mean and standard deviations of growing season irrigation for each simulated water usage scenario, as well as the reported water usage data in cubic meters per year for all 259 growing seasons used for comparison in this study.

Scenario	Mean Growing Season Irrigation (m^3)	Standard Deviation (m^3) (n=259)
Reported	60,489	50,534
1a	54,838	38,777
1b	51,485	36,481
2a	180,560	119,872
2b	126,218	83,770

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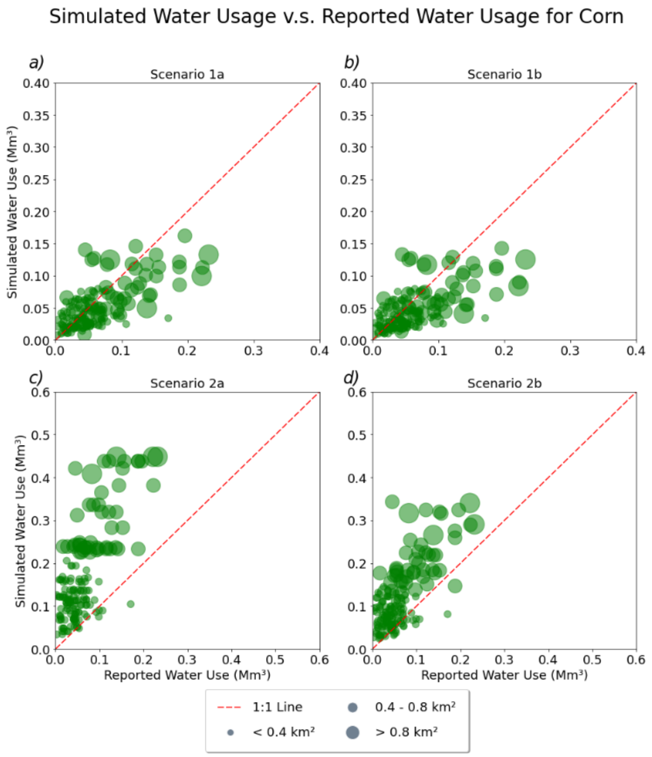

FIGURE 9: Scatterplots of simulated versus reported water usage for scenario 1a (a), scenario 1b (b), scenario 2a (c), and scenario 2b (d) for corn fields only. Circle size is related to field size, with larger circles representing larger fields. The red dashed line represents the "ideal fit" for the distribution.

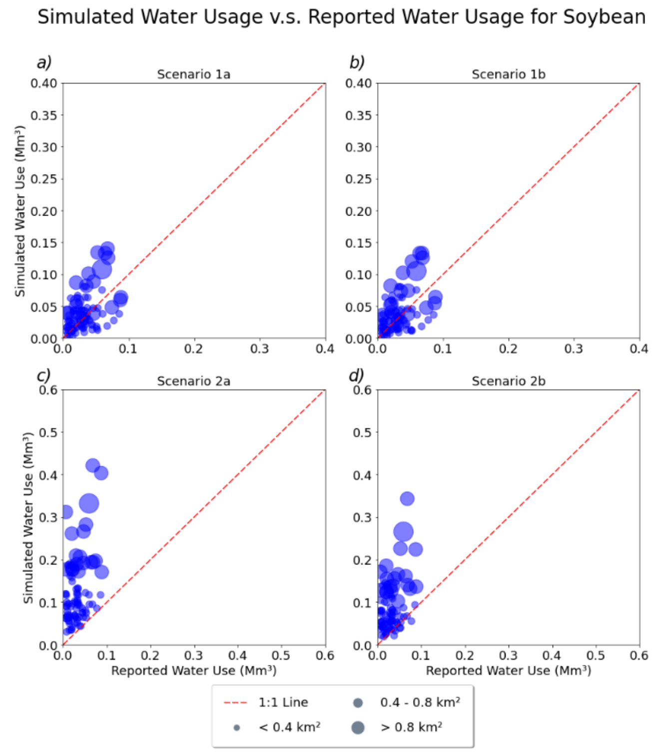

FIGURE 10: Scatterplots of simulated versus reported water usage for scenario 1a (a), scenario 1b (b), scenario 2a (c), and scenario 2b (d) for soybean fields only. Circle size is related to field size, with larger circles representing larger fields. The red dashed line represents the "ideal fit" for the distribution.

estimated by the model. Meanwhile, the calendar-based scenarios show a bias towards over predicting water usage, particularly scenario 2a (Figure 9c-d). This is further supported by the much higher r_c values for ET-based scenarios (1a and 1b) than calendar-based scenarios (2a and 2b) for "corn only" in Table 3. Figure 10a and 10b show the distribution of soybean fields centered around the 1:1 line for ET-based scenarios, though with a slight bias towards overestimating water usage. The calendar-based scenarios in Figure 10c and 10d show a large positive bias, whereby the model overestimates the amount of water used by soybean fields. Meanwhile, r_c values for ET-based scenarios are modest (0.414-0.428), though they show much better agreement than the calendar-based scenarios (0.077-0.121) for soybean fields.

4. Conclusions

Agricultural irrigation water usage in Delaware was simulated over a 10-year period using two irrigation decision making approaches: an ET-based approach, where a soil water availability threshold determined the frequency and amount of daily irrigation to apply, and a calendar-based approach where irrigation is applied at predetermined intervals based on *a priori* knowledge of a crop's anticipated growth. Each irrigation decision making approach was further divided into two scenarios, with the ET-based scenarios varying based on how much irrigation was applied (fixed versus variable) and the calendar-based scenarios varying based on the use of a rain gauge, which in scenario 2b was used to determine when to skip planned irrigation events. These scenarios were simulated using high resolution input datasets, including USDA SSURGO soils data, an irrigated farmland dataset for Delaware updated through 2018, high density weather data from the DEOS network, and seasonal crop type information from the USDA. In addition, crop emergence dates in the model were based on weekly crop condition reports from USDA.

Seasonal variability in irrigation water usage is affected by both the irrigation decision making process as well as environmental conditions. While seasonal rainfall and evapotranspiration are important factors in determining the amount of irrigation used in a growing season, the timing

TABLE 3: Comparison statistics for simulated versus reported water usage data for irrigated fields in Delaware from 2010-2019.

Group	Scenario	Mean Absolute Error (MAE) (m^3)	Mean Bias Error (MBE) (m^3)	Pearson Correlation Coefficient (r)	Concordance Correlation Coefficient (r_c)
ALL (n=259)	1a	24,735	4,705	0.622	0.596
	1b	25,827	7,498	0.579	0.538
	2a	100,958	-99,979	0.668	0.258
	2b	58,200	-54,731	0.654	0.398
Corn only (n=168)	1a	26,555	11,475	0.679	0.612
	1b	28,515	14,847	0.632	0.538
	2a	106,190	-104,681	0.713	0.290
	2b	58,828	-54,322	0.705	0.460
Soybean only (n=91)	1a	21,374	-7,792	0.468	0.414
	1b	20,866	-6,070	0.471	0.428
	2a	91,300	-91,300	0.356	0.077
	2b	57,041	-55,485	0.350	0.121

of the rainfall relative to the peak water demand of the crop is more important. For example, 2018 had the fourth highest irrigation water usage of all growing seasons simulated in the study while also having much above normal rainfall. Seasonal irrigation also varied spatially over the 10-year study period, primarily due to variability in the water holding capacity of soil types in Delaware.

Simulated irrigation water usage data from this study was compared to a high-quality reported water use dataset provided by DNREC. While none of the simulated irrigation scenarios perfectly matched the irrigation decision making behavior exhibited in the reported water use data, the simulation scenarios do capture the range of seasonal irrigation applied to corn and soybean in Delaware. Based on a correlation analysis and assessment of error, Scenario 1a, which used a fixed irrigation amount based on when a maximum allowed depletion (MAD) threshold was surpassed, provided the best estimate for irrigation water usage for corn and soybean in Delaware. The calendar-based scenarios provided a good reference for a worst-case management scenario by applying irrigation at high rates relative to the crops' actual water needs. While irrigation water use in Scenario 2a far exceeded the simulated irrigation water usage in the other scenarios, as well as reported irrigation water usage, Scenarios 2b, which skipped calendar prescribed irrigation applications when there was sufficient rainfall, provided more realistic values for seasonal irrigation water usage. By simulating irrigation under a variety of scenarios, this study provides a method for determining the potential irrigation water usage range at the field level for water resource managers in Delaware. This is a crucial step toward improving the allocation of limited water resources in Delaware in the future. Overall, the irrigation scenarios did well depicting irrigation water usage using only environmental conditions, despite the fact that irrigation decisions in practice are based on many factors.

Although this study was limited to Delaware (USA), it leveraged many datasets that have regional and national coverage which could be used to perform similar studies in other states, particularly the Mid-Atlantic region of the United States. Weather data used in the model are certainly more localized and came from a Delaware mesonet, however similar mesonets that calculate ET_o and measure precipitation exist in many other parts of the United States (Mahmood et. al, 2017), whose data could be used in the same fashion. Some mesonets even measure soil moisture and groundwater well levels, which can also provide additional datasets that can be used to refine and examine irrigation water usage estimates. Assuming a reasonably accurate and recent irrigated farmland spatial dataset is available, the approach demonstrated in this study could be used to estimate the range of irrigation taking place in other states and regions. Limitations in any study like this include the accuracy of the input datasets, particularly soil properties. Farm fields can have multiple soil types resulting in additional variability in their soil properties. While this study used a centroid method to identify the predominant soil type for a field, future studies could examine various spatial sampling of soil properties to determine if a more optimal irrigation simulation is possible. This study also demonstrated the need for more and better irrigation validation data. Despite the existence of nearly 3,000 irrigated fields in Delaware, slightly more than 250 individual field growing seasons were used for validation over the 10-year study period. Few states require or are able to utilize metered data from irrigation systems to estimate irrigation water usage. Even where metered data are available, proper installation and maintenance of the meter is essential to ensure data quality. Given the limited availability of high-quality irrigation water usage data and other validation datasets, modeled estimates of irrigated water use are essential to understanding the magnitude and range of potential irrigation water usage by agriculture and other sectors. Finally, as climate change and human activities intensify the demand for limited water resources, it is critical that states and other jurisdictions regularly conduct irrigation water usage studies to understand the potential for limits on those water resources (Flörke, et. al., 2018; Tukimat et. al., 2017; Chavez-Jimenez, et. al., 2015). Future work should examine these effects at the local level where many water resource management decisions (e.g., allocation, restrictions, etc.) are made.

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