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Improving water use efficiency of surface irrigated sugarcane

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Sugarcane (*Saccharum officinarum*) is a traditional major crop and export of Guyana. This study aims to assess the current irrigation scenario and propose scenarios to maximize the yield and water use efficiency of sugarcane (*S. officinarum*) in Guyana, using the AquaCrop model. Field-measured climate and soil data, and local crop parameters were used in the simulations. The crop simulations were calibrated with actual yields from 2005 to 2008. The calibrated parameters were then validated using the 2009 to 2012 yield dataset. The good agreement (RMSE of 7.15%) with the recorded yield during validation and the low sensitivity of calibrated parameters indicate the acceptability of AquaCrop and the parameters used for simulations. During calibration, the yield was weakly sensitive (0.6–2% ΔRMSEn) to changes in crop parameter values with the highest sensitivity observed for the maximum canopy cover (CCx) and the crop coefficient (kc_{max}). Several irrigation scenarios were then simulated, of which no significant reduction or increase in yield was observed between the scenarios 50% to 100% of the total available water (TAW). A threshold of 50%TAW is advised during dry periods to avoid significant yield loss. It is recommended that this scenario be validated with field experiments. The results of this study will assist in maintaining high sugarcane yields even during dry conditions.

KEYWORDS

AquaCrop, sugarcane, Guyana, irrigation management, water use efficiency, furrow irrigation, heavy clay

1 Introduction

Sugarcane (*S. officinarum*) is a traditional major export crop of Guyana. In Guyana, the first crop, called plant cane, is usually planted between November and January and is harvested after 40 weeks (Eastwood, 2009). A ratoon crop, which is grown from shoots left by the harvested crop, takes 36 weeks to be ready for harvest (Eastwood, 2009). Sugarcane is planted on beds in either a ridge-and-furrow or broad-bed design. Most of the fields have traditionally followed the ridge-and-furrow layout, but recently, more plots have been converted to broad beds for mechanized planting and harvesting (GuySuCo, 2018). Water is pumped from conservancies and rivers into the canals leading to the sugarcane estates. It is then routed into the furrows within the fields. The irrigation layout is a continuous open-ended furrow system wherein water is allowed to freely enter and exit the furrows. When water reaches the end of the furrows, it is collected by an in-field collector drain which routes and merges with the main canal network. With the current irrigation scheme, the soil-water content in the field is estimated to be maintained at 70% of total available water (TAW). Most of the agriculture sits along the coasts of Guyana, especially on the rich Hydraquents or "frontland" soils such as Tain clay, Whittaker clay, Corentyne clay, and Skeldon clay (FAO, 1966). Going further inwards are Medihemists or bog, peat and muck soils (GLSC, 2013) which are swamps and marshlands used as reservoirs or conservancies (Steele and Ramdin, 1980; GLSC, 2013). Except for the tidal flats, the riverain and frontland soils have a silty-clayey, or clayey to heavy clay texture. Heavy clays, which are the most common among Guyana's frontland soils (GLSC, 2004), are soils with a clay percentage above 60% (FAO, 2006). They are characterized by relatively high fertility, poor drainage, and waterlogging after heavy rain (GLSC, 2013). Drainage is a major challenge, and as such, various adaptation techniques are employed: an extensive surface drainage network, sugarcane varieties adapted to waterlogged conditions, façade drainage canals, drainage pumps, and dikes. Heavy clay is also characterized by pronounced soil swelling and the formation of deep cracks or gullies during wetting and drying cycles (Kodikara et al., 2002). These soils have a high field capacity (FC), but also a high permanent wilting point (PWP) compared to other soil textures, which results in low available water ranging between 110 and 160 mm per meter of soil depth (Syers et al., 2001; Ibrahim et al., 2002; Dinssa and Elias, 2021). This narrow range makes crops not only susceptible to surface ponding, but also to drought in the dry season.

Sugarcane can be grown in a variety of soil textures including heavy clays such as around the Burdekin River (Holmes, 2014) and Mackay Region (Biggs et al., 2013) in Australia, Grand-Terre in Guadeloupe (Chopin et al., 2015; Sierra et al., 2017), and Nansei Islands in Japan (Arakawa et al., 2021). When planted on heavy clays, sugarcane has a slower root elongation rate, at 28 mm day^{-1}, and shallower rooting depth compared to those planted in other soil textures (Glover, 1967 as cited in van Antwerpen et al., 2022). Breeding for tolerance to flooding (Dlamini, 2021; Kennedy, 2022) and subsurface drainage design (Ritzema et al., 2008) have been done to adapt and improve sugarcane growth on heavy clay soils. Regardless of soil texture, double-row furrow planting (Singh et al., 2022), subsurface drip irrigation (Sheini-Dashtgol et al., 2020), and mulching using dead crop residue (Adetoro et al., 2020) have proven to increase the water productivity of sugarcane. Water-saving scenarios are also one of the common irrigation management strategies to improve water use. Dingre and Gorantiwar (2021) studied the effect of water deficit on sugarcane planted on clay soil in a semi-arid climate under drip irrigation while Santos et al. (2019) studied surface drip irrigation over sandy loam soil in a humid subtropical climate. There are no studies yet on the impact of irrigation thresholds for sugarcane planted under furrow irrigation, specifically on heavy clay soils in a tropical climate. The specific characteristics of heavy clays, and the different wetting pattern of furrow irrigation makes it difficult to apply the results of existing studies to sugarcane estates in the coastlands of Guyana.

Crop models can simulate the impact of agricultural management decisions on sugarcane yield. Notable models for sugarcane are DSSAT-CANEGRO, AquaCrop, and APSIM-Sugar. DSSAT (Jones et al., 2003) and APSIM (Dias et al., 2019) are process-based models wherein sets of equations describe each process of plant growth, and these processes are linked by internal variables to form a general model to describe the overall growth. AquaCrop, meanwhile, is a crop-water-based model wherein water uptake drives plant growth (Steduto et al., 2009). The conversion of water to yield is governed by three equations calculating the water required for evapotranspiration, the water transpired into biomass, and the partitioning of the above-ground biomass into yield and non-marketable biomass (Steduto et al., 2012). Since AquaCrop is not process-based, it does not model each plant process including those involving crop stress; instead, stress coefficients are factored into the three core equations as a modifier (Raes et al., 2018). These stress coefficients are determined by the indicator parameters and the proximity of their value to stress thresholds. This characteristic allows AquaCrop to simulate the yield and irrigation requirement of sugarcane with fewer, easily measured crop parameters. Its use of conservative and default parameters; and templates for various crops, makes it convenient when information on the numerous model parameters is limited. AquaCrop fits the needs of our study since our crop data are agronomic information and not genotypic data. Moreover, the simulation results are meant to represent the sugarcane estates at the coast and not field-specific yields. For this larger-scale simulation where generalized representative values are needed, AquaCrop is the most suitable.

In a comparison study of crop models by Feleke et al. (2021), AquaCrop has shown satisfactory prediction of canopy cover and yield of maize compared to DSSAT-CERES, and APSIM-Maize for four maize varieties, and three soil textures (sandy clay loam, clay and loam) in Ethiopia, which has a tropical monsoon climate. There is no similar crop model comparison study for sugarcane. Nevertheless, the Feleke et al. (2021) study has strengthened AquaCrop's applicability to simulate crop growth in tropical areas. Furthermore, AquaCrop has been intensively used for research and was used to simulate sugarcane growth to understand the crop's response to projected climate change in Pakistan (Farooq and Gheewala, 2020; Alvar-Beltrán et al., 2021); identify a suitable deficit irrigation design in Khuzestan, Iran (Bahmani and Eghbalian, 2018); and predict the impact of a shifted crop calendar considering climate projections in Phu Yen, Vietnam (Lee and Dang, 2018). Heavy clays have distinct cracking and swelling characteristics that may be difficult to incorporate in model simulations. In a study on several landscapes including Cambisols, Vertisols, Luvisols, and Regosols, run-off was poorly simulated in AquaCrop when cracks were present; however, overall, the soil water content and crop conditions were simulated well in AquaCrop due to the moderate influence of runoff in the soil water balance (Dhouib et al., 2022).

The wet tropical climate (Peel et al., 2007) and clayey frontland soils (Braun and Derting, 1964; GLSC, 2013) of Guyana's coast place more emphasis on drainage for agriculture. The entire irrigation and drainage system of Guyana, the conservancies, and the sea walls were designed to prevent flooding of the low-lying coastal land, which is below sea level (US Army Corps of Engineers, 1998). Yet, the sugarcane estates are prone to agricultural drought because of the intrinsic high PWP of heavy clays, and the shallower rooting depth of sugarcane in these soils. Improvements in irrigation will help achieve better yield, improve water conservation and help the agricultural sector to be prepared for drought conditions. All of the sugarcane estates, about 44,500 ha (GLSC, 2013), are managed by the government under GuySuCo. More efficient water management by the managing organization will cascade to big changes in the coastal agricultural landscape. For the wider scientific community, the results of this study will contribute to the growing body of knowledge on the recommended irrigation thresholds of crops, especially for sugarcane on heavy clay soils. This study aims to: (1) improve the irrigation of sugarcane estates in Guyana by identifying

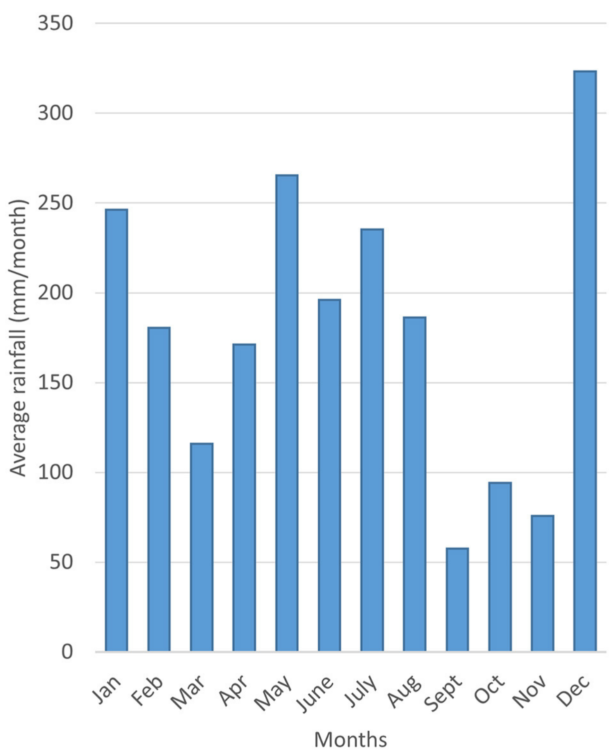

FIGURE 1
Average monthly rainfall (2005–2012) at the Region 6 sugarcane estates.

the impact of the current water management system on sugarcane yield and water use efficiency, and (2) Determine alternative irrigation water application scenarios to cope with dry conditions.

2 Methodology

2.1 Data and preparation of simulation files

The study location covers the sugar estates of Albion, Rose Hall, and Port Mourant in Region 6 along the Guyana coast. Sugar production in Albion accounts for 55% of Guyana's total production with 45,000 to 60,000 ha harvested annually from 2009 to 2018 (GuySuCo, 2018). Irrigation is mainly supplied by the Canje Creek which is located southwest of the sugarcane estates. Climate data were obtained from the nearest installed automatic weather station located at 6°4′58" N, 57°15′57" W. Daily data on the rainfall, sunshine hours, wind velocity, and minimum and maximum temperature were measured from 2005 to 2012. The average monthly rainfall at the study site, in Figure 1, shows variability between the months. A long, wet season can be observed from May to August and a short, wet season from December to January. The monthly rainfall varies between 50 and 200 mm. Minimum and maximum temperatures were almost constant throughout the year. The daily reference evapotranspiration (ETo) was computed using the FAO Penman-Monteith within AquaCrop.

The soil at the three estates is Frontland clay, more specifically, the drained phase of Corentyne clay. This soil series is a swampland soil which is prone to waterlogging during heavy rains but has high fertility (GLSC, 2004). It is non-acidic, and soft to moderately firm dark gray clay, with a firmer gray clay subsoil with yellowish mottles (FAO, 1966). Soil sampling at four random sites confirmed heavy clay soils with a sand-silt-clay ratio of 2%—34%—64%. The soil characteristics and soil water retention curve from the four sampling sites were measured. It has a bulk density of 1.11 g/cm^3. The percentage of soil moisture by volume at PWP across 3 depths (0–15, 15–30, and 30–45 cm) ranged from 32 to 35%, and the moisture content at field capacity varied from 49 to 51%.

The crop parameters used in the model were taken from the sugarcane file provided in AquaCrop. Default parameters for sugarcane can be found in the AquaCrop reference manual (Raes et al., 2018), with updated crop parameters published by Pereira et al. (2021). Field experiments in Brazil (da Silva et al., 2013; da Costa Faria Martins et al., 2022), Australia, Swaziland (Inman-Bamber and McGlinchey, 2003) and South Africa (Olivier and Singels, 2012) have contributed to improvements to key parameters of the sugarcane crop file, specifically the crop coefficients, maximum root depth, and the threshold of soil water depletion for water stress. When local values were available, such as those listed in Table 1, these values were prioritized and used in the model. Local field information ("F" in Table 1) includes locally measured parameters reported in the literature and field observations obtained by experts in Guyana. Parameters such as crop coefficient, growth duration, and threshold of water stress for stomatal closure were updated with information from Inman-Bamber and McGlinchey (2003), Eastwood (2009), Bastidas-Obando et al. (2017), Gaj and Madramootoo (2017), and Pereira et al. (2021).

To set up the soil moisture profile in the model, the soil moisture was initialized at saturation at the start of the growing cycle. This was because when planting cane points, the fields are irrigated first until saturated. To model water movement and availability in the soil, Aquacrop subdivides the soil depth into 12 compartments each of 0.1 m thickness (Steduto et al., 2012). Water and salt fluxes were computed at their boundaries by tracking irrigation, rainfall, evaporation, transpiration, run-off, capillary rise, and deep percolation. The daily rainfall, evaporation and transpiration were computed from the weather data. The sum of the water movements was the total soil water within the root zone. However, only the soil water between the field capacity and the permanent wilting point is available for plant use. This amount is denoted as the total available water (TAW) (mm/m) (Raes et al., 2018).

2.2 Calibration and validation

Without proper calibration, a model will produce yields which are different from actual values. A model must be calibrated so that its outputs are closer to reality. To calibrate a model, parameters must be adjusted. Calibration was done on 14 parameters by simulating several values for each parameter. During calibration, the irrigation scenario of 70%TAW was used. Key parameters which used local information were calibrated minimally to account for variation among the sugarcane estates, while parameters which

TABLE 1 Key simulation parameters and the values used.

Parameter	Value[a]	Source
Soil:		
Saturated hydraulic conductivity (Ksat)	35.0 mm/day	AQ
Curve number (CN)	77	AQ, Cal
Crop:		
Type of planting method	Transplanting	F
Row spacing	1.0 m	F
Plant spacing	0.25	AQ, Cal
Maximum canopy cover (CCx)	90%	AQ, Cal
Days to recovered	22 DAT	F, Cal
Days to max canopy	134 DAT	F, Cal
Days to harvest	281 DAT	F, Cal
Max effective rooting depth (Zx)	0.80 m	F
Days to max root depth	181 days	F
Crop coefficient at CCx (Kc_{max})	1.1	F, Cal
Water productivity (WP)	30.0 g/m^2	Con
Reference harvest index (HIo)	35%	AQ, Cal
p(upper) for stomatal closure (psto)	0.5	AQ, Cal
Aeration threshold below saturation	3%	AQ, Cal
Management:		
Irrigation method	Furrow	F
Water quality	0.0 dS/m	F
Weed cover	6%	F, Cal
Effect on CN by field practice	+10%	F, Cal
Simulation:		
Planting search window	Nov	F, Cal
Initial soil water	At saturation	F
Initial salinity	0.02 dS/m	F

[a]Key: Cal, Calibrated parameter; F, Local field observation or information; Con, Conservative parameter; AQ, AquaCrop default.

used AquaCrop values were also calibrated to make the parameters more representative of the Guyana coast. To consider uncertainty in the model values, a sensitivity analysis was done alongside calibration. We tested the effect of varying the values within a range provided in the literature, or within 10% of the default or average value. For each parameter, a value was chosen based on the best agreement between the simulated and the reported actual yields from 2005 to 2008. The actual yield data which was reported by GuySuCo (2013), was converted to dry yield using a 30% dry matter factor (Steduto et al., 2012). The agreement between the actual and simulated yield was determined through the root mean square error (RMSE), percent RMSE (RMSEn) and mean bias error (MBE). For example, for the parameter "maximum canopy cover", a value of "almost entirely covered (95%)" was the default based on the AquaCrop sugarcane file. The value "well covered (90%)" was also tested to see if it actually reflected the conditions in the field.

TABLE 2 Most sensitive calibrated parameters and range of values used with the corresponding ΔRMSEn.

Parameter calibrated	Range of values used	Δ RMSEn (%)
Crop coefficient at maximum canopy cover (kc_{max})	1.05–1.15	0.6–1
Maximum canopy cover (CC_{max})	90–99%	1–2
Days to maximum canopy	90–134 DAT	0.5–1
Days to harvest	267–295 DAT	0.5–1
Threshold for aeration stress	3–6% MC_{vol} below SAT	0–0.8%
Reference Harvest Index (HI_o)	34–36%	0–0.5%

TABLE 3 Agreement between simulated and actual yield after calibration and validation.

Simulation	RMSE	RMSEn	MBE
	ton cane/ha[a]	%	ton cane/ha[a]
Acceptable at:	<6.24	<10	<6.24
Calibration: 2005–2008	4.32	6.83	- 0.03
Validation: 2009–2012	4.39	7.15	+ 1.44

[a]In metric tons cane of fresh yield per hectare.

The simulated yield for 95% had an RMSE of 1.90 ton/ha, RMSEn of 10.03% and MBE of +0.98 ton/ha when compared with the reported yield. Meanwhile, the set which used 90% had an RMSE of 1.64 ton/ha, RMSEn of 8.65% and MBE of +0.71 ton/ha. These lower values signified less error between the simulated and reported yields for 2005 to 2008, which led to a final calibrated value of 90% for the maximum canopy cover. Additional calibration of other parameters was done to further improve the agreement between the simulated and reported yields. An RMSEn value below 10% signifies that the parameters used were acceptable for simulating yield. Once the calibrated parameters were finalized, they were validated by simulating the yields for 2009 to 2012, and computing the RMSE, RMSEn, and MBE values for comparison between the simulated and the reported yields for the Region (GuySuCo, 2013). Same as with calibration, an RMSEn value below 10% confirms that the parameters have been successfully validated for simulating the yield.

2.3 Irrigation management scenario simulations

The irrigation scenarios were all continuous open-furrow irrigation with varying thresholds in terms of the total available soil water in the root zone (TAW). There were seven scenarios simulated, namely, 40, 50, 60, 70, 80, 90, and 100%TAW. Irrigation commenced when the threshold was reached, and irrigation was provided to maintain the %TAW above the threshold. The 100%TAW scenario corresponds to soil water content maintained at field capacity. Simulations were run for each scenario from 2009 to 2012 using the validated crop parameters.

3 Results and analysis

3.1 Yield modeling

Before calibration, the simulated yields for 2005 to 2008 were overestimated by 6.7 metric tons ha^{-1} or 10.6% compared to reported yields. During calibration, the error of the simulated yield was reduced by as much as 2% upon calibration of the crop coefficient (kc_{max}; Table 2). After calibration, the simulation error decreased to an MBE of 0.03-ton cane ha^{-1}, and RMSE of 4.32-ton cane ha^{-1} (RMSE) which is equivalent to 6.83% of the average actual yield (Table 3). The calibrated parameters were then run from 2009 to 2012 for validation. Statistical analysis showed good agreement between the simulated and the actual yield with an MBE of +1.44 metric tons/ha and an RMSE of 4.39 metric tons/ha, which is equivalent to 7% of the reported yield.

3.2 Irrigation management scenarios

Each irrigation scenario was run from 2005 to 2012 to get simulated yields. An ANOVA of the yields shows that there is a significant difference among the scenarios (f-test, $p < 0.05$). The yield increased with increasing %TAW and plateaued at 80%TAW with 63-ton cane/ha, as shown in Figure 2. A lower mean yield was predicted at 50%TAW, however, a one-way t-test shows that the yield distribution at 50, 60, 70, 80, and 90%TAW is not significantly different from 100%TAW. The t-test compares not only the mean values but also the spread of the yield distribution considering variability in the weather. The 100%TAW was used as a reference since in this scenario, the soil is at field capacity, water stress is not present, and the highest yield was obtained. There was a statistically significant reduction in yield at 40%TAW. The irrigation requirements were also simulated and shown in Figure 3. Irrigation requirements decrease with a lower maintained %TAW.

Water productivity (WPet) is the yield produced per unit of water used for evaporation and transpiration (Steduto et al., 2012). The 60%TAW obtained the highest mean Wpet of 1.64 kg of dry biomass produced for each cubic meter of water used by evaporation and transpiration. However, both a one-way ANOVA and pairwise t-tests have confirmed that the differences in water productivity between all scenarios were minimal and not significant $p > 0.05$.

4 Discussion

4.1 Calibration and validation

The crop yield modeling provides important insights for forecasting yield and identifying impacts of stressors and management decisions. While there is statistical confidence in the changes in yield due to varying irrigation conditions, there is uncertainty in the exact value of projected yield because of inherent variability in the weather, spatial variability in the region, deviation from assumed values, and inherent errors in the model. By calibrating the model parameters to sugarcane cultivation in Guyana, we increased confidence in the results of AquaCrop. Without calibration, the simulated yield at 70%TAW, the current irrigation scheme, did not correctly represent the actual yield. The calibration of parameters led to a predicted yield error of 6.83% of the average actual yield. With an RMSEn of 7%, the validation conducted over a different set of years established the reliability of the model and the parameters used. The RMSEn falls within the range of error obtained in similar sugarcane validation studies using AquaCrop, such as by Alvar-Beltrán et al. (2021) who got an RMSEn of 11.6% for the yield of sugarcane in Pakistan; and Wellens et al. (2021) who obtained an RMSEn of 6.4% for biomass of sugarcane in Senegal. Another calibration-validation study by Jones and Singels (2018) using DSSAT-CANEGRO obtained an RMSEn of 23.46% for the aerial dry mass of sugarcane growth in South Africa. In our study, the AquaCrop model was observed to be most sensitive to changes in the values of the crop coefficient (kc_{max}) and maximum canopy cover (CC_x) with the resulting RMSEn fluctuating between 0.6 and 2% (Table 2). These values were quite minimal and suggest that the crop parameters used before calibration were already representative of the conditions in the field. Notably, in Table 1, kc_{max} was a field-measured value provided in the Agriculture Operation Guidelines of GuySuCo (Eastwood, 2009). Meanwhile, the CC_x was taken from the AquaCrop sugarcane base file.

4.2 Irrigation management scenarios

An increase in water productivity or a decrease in the irrigation water can improve the irrigation water use efficiency. We inspected first the WPet wherein there was no significant difference observed between the seven irrigation scenarios. The low irrigation scenarios do not increase nor decrease the water productivity of sugarcane in the Guyana coastal plains, but these scenarios could be as productive as full irrigation. The WPet can be improved through management practices which reduce evaporation, such as the application of soil amendments or mulches (Zahra et al., 2021; Kalanaki et al., 2022), shift to subsurface drip irrigation (Aydinsakir et al., 2021), crop rotations (Araya et al., 2017), and shift to alternate furrow irrigation (Mintesinot et al., 2004). These methods could be explored to improve the water productivity of sugarcane in Guyana. Table 4 shows a summary of irrigation studies on sugarcane with the recommended soil water thresholds, to achieve optimal water use and yield for different agro-climatic areas. Similar to our results, the water productivity, whether based on evapotranspiration (WPet) or transpiration (WPtr), was not significantly increased by reduced irrigation (Santos et al., 2019; Jamnani et al., 2022). Tayade et al. (2020) have shown a yield reduction in WPet between 100% and 50%. In cultivar studies (Coelho et al., 2018; Santos et al., 2019; Contiliani et al., 2023), an increase in water productivity has been observed between the interaction of deficit irrigation and sugarcane cultivar. The development of cultivars adapted to dry conditions is a more definitive method for increasing

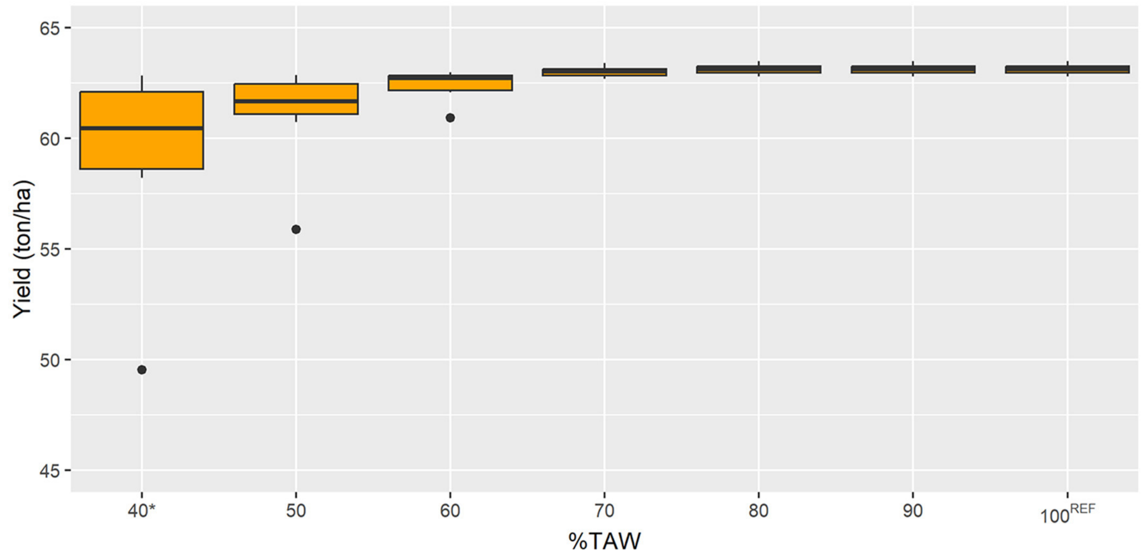

FIGURE 2
Simulated yield (ton cane ha^{-1}) obtained at varying %TAW scenarios.

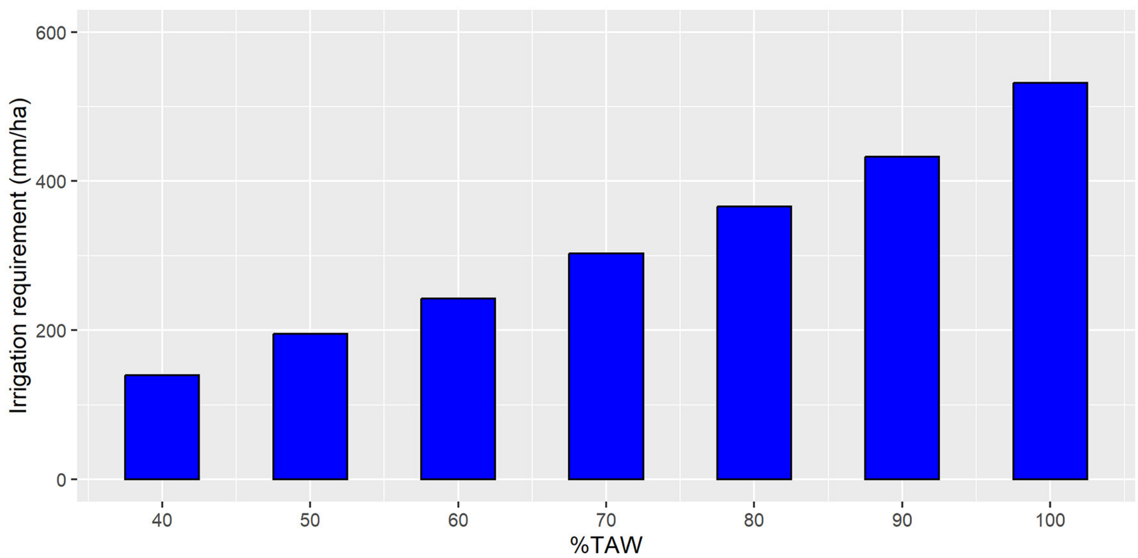

FIGURE 3
Irrigation requirement (mm ha^{-1}) of each irrigation scenario.

the water productivity of sugarcane compared to water-saving irrigation scenarios.

The second means of improving water use efficiency is to decrease the irrigation water provided while maintaining the yield. Lower irrigation thresholds such as 90, 80, 70, 60, 50, and 40% TAW, reduced the water use of each scenario. The scenarios between 80 and 100%TAW obtained the highest mean yield. The yield decreased below 80%TAW, but these changes were not statistically significant until 50%TAW. At 40%TAW, a significant ($p < 0.05$) yield penalty could be obtained. In Table 4, other sugarcane modeling studies on limited irrigation show that cane yield was not significantly reduced by some irrigation treatments (Bhingardeve et al., 2017; Bahmani and Eghbalian, 2018; Coelho et al., 2018; Dingre and Gorantiwar, 2021; Júnior et al., 2021; Jamnani et al., 2022). However, the threshold where the yield starts to significantly decrease is not consistent between these studies since the differences between their sites' soil texture and climate affect soil-water storage and the frequency of soil-water replenishment by rainfall. However, the different soil, climate and irrigation set-ups of the studies make it difficult to form a general conclusion regarding the appropriate irrigation threshold for sugarcane. In some of the reported studies (Dingre and Gorantiwar, 2021; Jamnani et al., 2022), when the soil-water was below a threshold (e.g. 60%TAW), an irrigation depth equal to the difference between 100%TAW

TABLE 4 Water-saving irrigation studies on sugarcane.

Recommended soil-water thresholds	Water treatments	Location	Soil	Climate
Dingre and Gorantiwar (2021) *Highest yield obtained at 100%TAW *Best irrigation combination: 100%TAW at tillering, 70%TAW at grand growth, and 40%TAW at maturity *Among the continuous treatments, the 70%TAW was recommended during water scarcity.	Drip irrigation Treatments: 0, 30, and 60% of TAW applied at tillering, grand growth, and maturity	Maharashtra, India	Clay	Semi-arid/subtropical
Santos et al. (2019) *Irrigation levels tested had no sig. impact ($p < 0.05$) on water productivity based on transpired water (WPt) and harvest index. *Irrigation level and genotype interaction had sig. impact ($p < 0.05$) on WP	Drip irrigation Treatments: 100, 75, and 50% of the potential water demand of each variety (914–1,025 mm per growing season)	São Paulo, Brazil	Sandy loam	*Done indoors.
Bahmani and Eghbalian (2018) *Recommended threshold: 85% of daily ETo *No significant difference in yield between 100, 125, and 85% scenarios	Treatments: 100, 125, 85, and 70% of the ETo calculated from evaporation pan (US Class A)	Khuzestan, Iran	Clay loam	Hot desert/hot semi-arid
Coelho et al. (2018) *Deficit irrigation, at 45 days before harvest, had significantly ($p < 0.01$) reduced brix, juice polarization, fiber, and cane polarization; but increased stalk yield. *Deficit irrigation and cultivar interaction had an impact ($p < 0.05$) on stalks per hectare, stalk yield, and sugar yield.	Subsurface drip irrigation Treatments conducted 45 days before harvest: 1. No irrigation 2. Irrigated by 50% ETc when ETc depth is reached	São Paulo, Brazil	Heavy clay	Humid subtropical
Jamnani et al. (2022) *No significant difference in yield, and WPet across treatments. *The economic productivity of Scenarios 2, 3, and 4 was significantly higher than Scenario 1. *Scenario 3 was recommended for normal years, while Scenario 4 was for dry years.	Scenarios: 1. Depth and interval of current irrigation schedule 2. At 40–55%TAW, irrigate back to field capacity (FC) 3. Interval of Scenario 1 and irrigated back to FC 4. Interval of Scenario 1 and water deficit with 5% yield loss	Khuzestan, Iran	Silty clay, silty clay loam, clay	Hot desert/hot semi-arid
Júnior et al. (2021) *The 60%ETc treatment was recommended considering sugarcane technological indexes.	Treatments: 100, 80, 60, 40, 20, and 0% of the ETc for five cultivars	Goiás, Brazil	Latosol peat, and sand	Tropical savanna
Bhingardeve et al. (2017) *The 60%ETc produced the same yield for plant cane as the 80%ETc which produced the highest yield for both plant cane and ratoon. *Higher yield and millable cane height at 2 days irrigation interval	Treatments: 80, 60, and 40%ETc depth at 2-, 3-, and 5-day irrigation intervals under subsurface irrigation Control: surface irrigation	Maharashtra, India	Clayey	Tropical monsoon
Tayade et al. (2020) *The 100%ETC gave a significantly higher yield than both 50%ETc treatments. *Significant reduction in the WPet of the 50%ETC treatments compared to 100%ETC.	Treatments: 100% ETc, 50%ETc, 50%ETc alternate irrigation	Coimbatore, India	Sandy clay	Hot semi-arid

and the threshold was applied. In other studies (Bhingardeve et al., 2017; Bahmani and Eghbalian, 2018; Santos et al., 2019; Tayade et al., 2020), the threshold of soil water content was not used; instead, a deficit was applied to the irrigation required for full irrigation, i.e., a 60%ETc treatment means that the irrigation provided was 60% of the 100%ETc treatment. The work of Dingre and Gorantiwar (2021) is most similar to our study in terms of the TAW and irrigation set-up. They evaluated 100, 70, and 40%TAW thresholds, wherein a significant reduction in yield was observed at the 40%TAW, like our study results. Regardless of the differences in methods and agro-climatic environment, the studies were conclusive that water-saving irrigation treatments can reduce irrigation water consumption at no significant reduction in the yield of sugarcane.

We are proposing a lower irrigation threshold wherein 50%TAW is the maintained soil-water content. There are other measures to manage irrigation when water is limited such as full irrigation of a reduced planted area (Ostad-Ali-Askari et al., 2017), and alternate furrow irrigation (Mintesinot et al., 2004; Tayade et al., 2020). The choice of furrow irrigation management to implement would benefit from an economic analysis which will consider the price of goods offered, the predicted yield and brix of sugarcane, and costs of water, labor, and materials.

4.3 The case of El Nino years

Among the years studied, the 2007 and 2010 growing periods received the lowest rainfall. These years coincide with the weak El Nino from Aug 2006 to Feb 2007, and moderate El Nino from June 2009 to April 2010 (NOAA, 2023). For both El Nino periods, using the current irrigation scheme at 70%TAW, at least 2,980 cubic meters of irrigation water per hectare are required for one whole growing season. The bulk of this irrigation volume was required between January to March when the sugarcane was at the tillering stage. Even in normal years, irrigation is necessary during these months for high yield. During the El Nino, these months became drier, and consequently, the irrigation requirement increased. Tillering is not the most water-intensive stage of sugarcane, however, water stress received during this stage has a significant impact on the yield compared to grand growth or maturity stages (Dingre and Gorantiwar, 2021). The next stage, the grand growth stage, is the most water-intensive stage due to its long duration and the development of the crop's full canopy (Eastwood, 2009). It starts in March and ends around July. The rainfall during these months is normally high and well-distributed, as shown in Figure 1. With the El Nino, even with reduced rainfall during these months, irrigation was not as crucial as that required during the tillering stage. Alternative irrigation methods, such as block scheduling or deficit irrigation, while maintaining the soil water content to at least 50%TAW could be applied from January to March if irrigation water supplies are limited. Moreover, the 50%TAW irrigation can already be started around November or December to increase stored irrigation water in the conservancies in anticipation of the dry conditions from January to March. Another method is to reduce the planting area of sugarcane based on the projected hectarage which can be fully irrigated during the tillering stage (January to March).

5 Conclusion

Irrigation management scenarios were simulated for sugarcane grown along the Guyana coastal plains on heavy clay soil. The sugarcane crop file of AquaCrop was successfully calibrated with reported yields from 2005 to 2008 and validated with yield data from 2009 to 2012. During calibration, the simulated yield did not show high sensitivity to changes in the values of crop parameters. The good agreement between the simulated and the reported yields during both calibration and validation showed that AquaCrop and its corresponding sugarcane crop file can be used to reliably simulate yields when used with field-measured soil and climate data, and key crop parameters: maximum canopy cover, crop coefficient, days to maximum canopy, and days to harvest.

Sugarcane yield at the current irrigation of 70% of the total available water (TAW), was compared with other irrigation management scenarios of 40, 50, 60, 80, 90, and 100%TAW. The yield was highest at 80%TAW to 100%TAW. An irrigation scenario of 70%TAW provides high yields and optimal water use. Keeping the soil-water content above 70%TAW uses more irrigation water, with minimal or no increase in the yield. Meanwhile, by using the 50%TAW threshold, yield is still not significantly affected and water use can be reduced by 63% compared to field capacity. This makes this irrigation scenario a viable management threshold during dry conditions when irrigation water is scarce. It is recommended to conduct field tests with the 50%TAW threshold to validate the yield.

A relationship between the hydraulic head maintained at the main irrigation channel regulator and the moisture level at 70%TAW in the field also ought to be determined to control the moisture in the fields, as it will further help understand the wetting pattern at the driest downstream sections of the fields.

Data availability statement

The datasets presented in this study can be found in online repositories. The names of the repository/repositories and accession number(s) can be found at: https://doi.org/10.6084/m9.figshare.23802297.

Author contributions

GM: Data curation, Formal analysis, Investigation, Methodology, Validation, Visualization, Writing—original draft, Writing—review & editing. CM: Conceptualization, Formal analysis, Funding acquisition, Methodology, Resources, Supervision, Writing—review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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