Long-Term Simulations of the Hydrology for Sugarcane Fields in the Humid Tropics: Case Study on Guyana's Coastland

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Abstract: A 4.2-ha sugarcane field in Guyana was instrumented to measure hydrometeorological variables and water table depths in order to calibrate DRAINMOD. The model performs favorably, with a Nash–Sutcliffe model efficiency (NSE) of 0.72, index of agreement (IoA) of 0.92, mean absolute error (MAE) of 16.5 cm and percentage bias (PBIAS) of 1.0%. DRAINMOD is then used for long-term simulations of the field hydrology using historical climate data. The simulated field discharges are used to compute average drainage rates (DR) for five durations (1-day, 2-day, … , 5-day). The annual maximum drainage rates for each of the five durations are then fitted to the Gumbel distribution (EV1) for frequency analysis. The return period for an average 3-day (DR3) duration drainage event is estimated, and it is shown that the historical design drainage coefficients (35–50 $\mathrm{mm\,day^{-1}}$) used for surface drainage systems in sugarcane fields along Guyana's coastland have return periods ranging from 1 in 2 years to 1 in 5 years. These return periods are within recommended values commonly used for agricultural drainage systems. **DOI: 10.1061/(ASCE)IR.1943-4774.0001204.**

Author keywords: Discharge; Drainage rates; Hydrology; Simulations; Return period.

Introduction

Hydrologic and water quality models are used for evaluating the impacts of climate, land use, and agricultural management practices on land and water resources (Moriasi et al. 2012). These models have been successfully applied to the design of drainage and irrigation systems for improved agricultural productivity. One such model, DRAINMOD, is a field-scale hydrologic model that was primarily developed for poorly or artificially drained lands (Skaggs 1978; Skaggs et al. 2012). The model is based on water balances conducted in the soil profile and on the soil surface. Importantly, hydrologic conditions in fields with single, nonparallel, and/or surface drains can be simulated by calibrating the drain spacing (L) and using a virtual tile drain system (Amatya et al. 2003; He et al. 2002). DRAINMOD is evaluated mainly by the output variables such as water table depths and drainage volumes. The model has been successfully applied and evaluated for water table management studies of sugarcane production in the United States and Australia (Carter et al. 1988; Gayle et al. 1985; Yang 2008).

In Guyana, sugarcane production presents a unique case for water management as a result of the country's climate, soil type, and topography. The crop is grown on the narrow strip of coastline that borders the Atlantic Ocean. The general topography of this region is flat and it lies between 0.5 and 1.0 m below mean sea level (Dalrymple and Pulwarty 2006). As such, sea and river defence systems in the form of dams, canals, and sluices were employed by the Dutch settlers in the early eighteenth century to reclaim the coastal lands and prevent flooding and intrusion of the sea (Lakhan 1994). The soils in this region are alluvial clays that are rich in nutrients and are ideally suited for agriculture once adequately drained. However, these heavy clay soils become easily waterlogged after wetting from precipitation events, and drainage becomes a major challenge for water management. To further exacerbate the problem, the local climate in the coastal region is wet tropical, with an annual average precipitation of 2,300 mm. This is unevenly distributed throughout the year—almost 50% occurs during the long wet season from May to July, and 22% occurs during the short wet season from December to January (Potter 1970). Furthermore, this uneven rainfall distribution creates water surpluses during the wet seasons and moisture deficits in the dry season, justifying the need for good water management practices for sustainable crop production.

Waterlogged conditions adversely affect sugarcane yields; Carter et al. (1988) demonstrated that water table management is key for optimizing yields. In addition, saturated conditions reduce field-machine trafficability in areas where the soil type is predominantly a heavy clay, as is the case for Guyana. Therefore land preparation works are affected, causing delays to the sugarcane cropping schedule. These factors highlight the need for an effective and efficient drainage system to reduce flood damage.

Historically, the drainage systems for these sugarcane plantations in Guyana were designed as surface drains with a design drainage coefficient ranging from 35 to 50 $\mathrm{mm\,day^{-1}}$. These coefficients were derived from extreme-value distribution analyses of rainfall for a 3-day storm with a return period of 2 years (Eastwood 2009). However, these analyses were based on data prior to 2002, and recent flood events from prolonged periods of intense rainfall between 2004 and 2005 (UNDAC 2005) suggest a need to update these design drainage coefficients. The total damages and losses from the 2005 flood were estimated at US$448 million, which was approximately 59.5% of the Gross Domestic

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Product (Economic Commission for Latin America and the Caribbean, unpublished report, 2005). Furthermore, the design surface drainage coefficients have not been verified by long-term experimental work, and their adequacy needs to be evaluated.

DRAINMOD can be used to analyze the hydrology and drainage of agricultural lands on Guyana's coastal region and assess drainage effectiveness using long-term climatic data. This paper presents an application of DRAINMOD in which the simulated outputs were used to evaluate the frequency of total field discharge for various durations from sugarcane lands along the Guyana coast. To this end, the objectives of this study are to (1) calibrate DRAINMOD for application to sugarcane fields in Guyana, (2) simulate long-term field hydrology using historical climate records, and (3) evaluate various simulated drainage rates using frequency analysis.

Materials and Methods

Site Description, Drainage System, and Crop Management Practice

Experiments were carried out on field CM 57 at La Bonne Intention (LBI), Region #4, Guyana, one of the eight sugar estates of the Guyana Sugar Corporation (GuySuCo). The field is 4.2 ha with average dimensions of 386 m in length and 110 m in width (latitude 6° 46′ 20.13″ N; longitude 58° 04′ 38.82″ W). The soil type for the field is classified as the Whitaker Series—37, which is characterized by poor drainage properties (Steele 1966).

The field is empoldered with earthen dams which virtually makes it an isolated hydrologic unit. Fig. 1 shows the site plan and the layout of the drainage system with the peripheral canals and dams. The canals on the northern and southern sides are cross canals, and on the eastern side there is a navigation/irrigation canal (Middlewalk). These three canals are interconnected and a constant water level of 15.94 m relative to the Georgetown Datum (GD) is maintained throughout the year by GuySuCo. The fourth canal on the western side is the main drainage canal (Sideline) which collects the discharge from the field via the internal field drain (triangular open ditch). This field drain runs longitudinally in the middle of the field, sloping (0.14%) westward as shown in Fig. 1. The average width and depth of the field drain are 94 and 40 cm, respectively.

The land also slopes gently (2%) toward the internal field drain on each side. A system of ridges and furrows were formed along these transverse slopes and the sugarcane stalks are planted on the ridges. The ridges are spaced at 1,520 cm apart and are approximately 18 cm in height. The cane stalks are placed at 60 cm intervals along the length of each ridge. All surface runoff from the furrows is routed toward the internal field drain, resulting in very little to no ponding on the surface. Surface runoff collected in the internal field drain is then routed to the Sideline drainage canal through the 45-cm diameter high-density polyethylene (HDPE) pipe culvert.

The main commercial sugarcane varieties planted on CM 57 are DB7869 and DB75159, which were planted on October 6, 2009 after the last fallow. The first crop (plant cane) was harvested in February, 2011 and the second crop (first ratoon—1R cycle) was harvested in October, 2012. The second ratoon stage (2R cycle) or third crop started on November 1, 2012 and lasted throughout the experimental phase of this research. The third crop was ready for harvesting by November, 2013 at which time all field instruments had to be removed.

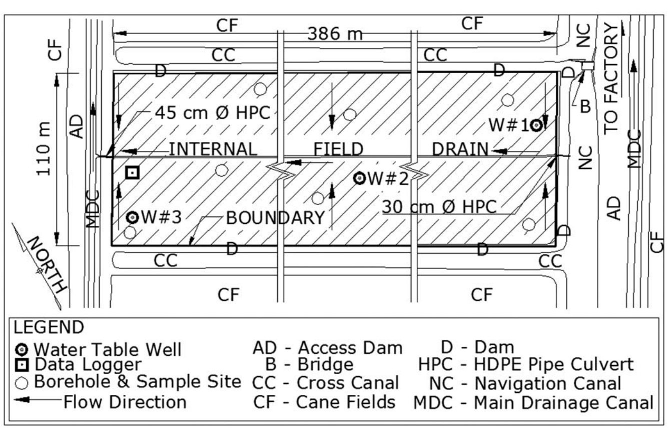

Fig. 1. Site plan of field CM 57 showing the layout of the surface drainage system and location of the field instruments

Field Instrumentation

The field was instrumented with an automated weather station to measure several hydrometeorological parameters required for calibrating DRAINMOD. These parameters included precipitation (P), air temperature (T), relative humidity (RH), solar radiation (Rs), wind speed (U), and soil moisture (S). Electronic sensors for each parameter were connected to an Onset Hobo U30/GSM data logger, installed at the site with a solar panel providing the necessary power input. The above parameters, with the exception of P and S, were used as input for the computation of reference evapotranspiration (ET_o) based on the FAO-56 Penman Monteith evapotranspiration (ET) model (Allen et al. 1998). This was done using the FAO's *ETo Calculator* (Raes 2012). The program computed ET_o which was then converted to crop ET (ET_c) by applying the single crop coefficient (K_c) for sugarcane at the various growth stages as detailed in Allen et al. (1998). The crop coefficient considers both physical and physiological characteristics for crops at specific periods in their growth stages. For sugarcane grown in a tropical region, Allen et al. (1998) listed the following K_c values for ratoon crops: 0.4 (initial stage), 1.25 (mid stage), and 0.75 for the late stage. Corrections to these coefficients are needed to adjust for local U and RH. However, the sugarcane ratoon crop (2R cycle) was already in its mid stage when data collection started, and hence no modification to K_c for the initial stage was needed. The mid-stage K_c was adjusted to 1.15 after correcting for local U and RH. Finally, a K_c of 1.25 was used for the late stage as recommended by Inman-Bamber and McGlinchey (2003).

Additionally, two KPSI 700 submersible level pressure transducers (Measurement Specialties, South Burlington, Vermont) were used to record the water levels at the headwater and tailwater sections of the 45-cm diameter HDPE pipe culvert. This was done to compute the total field discharge from the field indirectly using culvert hydraulic formulae as given by the U. S. Geological Survey (USGS) (Bodhaine 1968). However, backflows from the Sideline drain into the field were observed for prolonged periods during the wet season and this prevented reliable estimates of daily field discharges. Ultimately, daily drainage volume data could not be used to augment the calibration of DRAINMOD.

Water table depths were monitored during the study period and used as the primary variable for the calibration of DRAINMOD. Three observation wells were installed along a diagonal in the field (Fig. 1) by augering holes (4-cm diameter) to an average depth of 1.5 m. Perforated polyvinyl chloride (PVC) pipes were installed as a well casing and housing for electronic loggers to record the water table depth in the wells. A Solinst Model 3001 Levelogger (Ontario, Canada) with built-in logging and storing capabilities was placed in each well to record the water depths at 10-min intervals. Additionally, a compensating Barologger (Solinst) was installed and used to correct the readings on the Leveloggers for atmospheric pressure. Water table depths were logged from March 16 to November 19, and the hydrometeorological parameters were logged from March 16 to November 26, 2013.

Soil Investigation

A soil investigation was undertaken to determine the physical properties and characteristics of the soil at the field site. Three test pits were dug to identify the underlying soil strata. Four distinctive layers to a depth of approximately 1.5 m were observed in the test pits and representative samples were taken from each layer for laboratory testing. Disturbed samples were used for several lab tests as follows: Atterberg limits [ASTM D4318-00 (ASTM 2000a)], particle size analysis [ASTM D422-07 (ASTM 2007)], specific gravity [ASTM D854-02 (ASTM 2002b)], and water content [ASTM D2216-98 (ASTM 1998)]. Undisturbed samples were obtained for measuring the soil-water characteristics [ASTM D6836-02 (ASTM 2002a)] and bulk density [ASTM D2937-00 (ASTM 2000b)] of the soil.

Field saturated hydraulic conductivity (K_{sat}) was determined in situ using the Hooghoudt auger-hole method (Beers 1983). The complete standardized auger-hole method test kit from Eijkelkamp (Giesbeek, Netherlands) was used to determine the K_{sat} values for Layers 2 and 3 of the four-layer soil profile. The logistics of transporting the bulky and heavy test kit to the field site did not allow for the other two layers to be tested because it was difficult to access the field during the wet season. However, the K_{sat} values for Layers 1 and 4 were calculated based on particle size and bulk density using the equation developed by Jabro (1992). Yang (2008) adapted the equation to local conditions for use in DRAINMOD by adjusting the constant. Applying this methodology yielded the following relationship:

$$\log K_{sat} = 8.91 - 0.81 \log(\text{silt\%}) - 1.09 \log(\text{clay\%}) - 4.64(\text{BD}) \quad (1)$$

where K_{sat} = computed saturated hydraulic conductivity (cm h^{-1}); silt% and clay% are from the particle size distribution; and BD = bulk density (g cm^{-3}). The percentage error between the measured K_{sat} and the computed K_{sat} from Eq. (1) was 0.14% for Layer 2, which was used to make the adjustment.

Calibration and Input Parameters for DRAINMOD

DRAINMOD was calibrated using the average observed water table depths from the three wells installed in the field. Although data collection started in March, 2013, the evaluation period commenced from April 1 because the wells were dry on several occasions prior to that date. Effectively, the calibration period from April 1 to November 19, 2013 spanned water table depths in the long wet and long dry climatic seasons experienced on Guyana's coastland. It is worth noting that no continuous record of water table depths or flow discharges for sugarcane fields in Guyana currently exist, and therefore model validation could not be performed in this study.

The main input parameters for calibrating DRAINMOD can be categorized as weather data, soil data, drainage system, and crop data. The input weather files were created from daily rainfall and minimum and maximum temperature measured at the experimental site. DRAINMOD computes ET as a two-step process using the Thornthwaite (1948) temperature-based model and the limiting conditions of soil-water availability (Skaggs 1980). However, this is usually adapted for local conditions by adjusting the monthly ET factors (Skaggs et al. 2012). The corrected monthly ET factors were computed as the ratio of potential ET (PET) (Thornthwaite 1948) to the ET_o (FAO PM-56) using the measured meteorological data from the experimental site. Weather data from the Georgetown Botanical Gardens meteorological station located 8.5 km west of field CM 57 were used as a supplement for all other days in 2013 outside the March-to-November data collection period.

The input soil data included the soil-water characteristics, the saturated hydraulic conductivity, and the lateral saturated hydraulic conductivity. These soil parameters introduce the largest uncertainty in DRAINMOD's output (Wang et al. 2006). Hence every attempt was made to measure representative field values for these soil properties. The soil-water characteristic curve (SWCC) for each of the four soil layers was generated from the laboratory test results on the undisturbed soil samples. The lateral saturated hydraulic conductivity was approximated as twice the K_{sat} value for each soil layer after the parameter was tested for sensitivity. DRAINMOD used these data to generate the drainable porosity for the soil profile, and these were adjusted during calibration.

The drainage system parameters for DRAINMOD include the spacing of the drain and its depth from the soil surface. Because there were no tile drains in the field, a virtual tile drainage system was assumed for the model calibration following the work of He et al. (2002). This approach has been justified by the model developers as a method for adapting DRAINMOD to fields without a parallel subsurface drainage system. DRAINMOD was originally developed for agricultural fields on poorly drained coastal soils with shallow water table depths, and its ease of calibration with minimal data sets explains its popularity and widespread use as a hydrological model (Amatya et al. 2003; He et al. 2002; Skaggs et al. 2012). For the calibration, a drain spacing of 40 m and average internal field drain depth of 40 cm were chosen as the initial parameters, which were adjusted during calibration. The initial distance to the impermeable layer was estimated at 2.6 m, and this was adjusted during calibration. Noncalibrated parameters included the drainage coefficient of 50 mm day^{-1}, which was the upper limit of the historical design DC used for the existing surface drainage system, and the maximum surface storage of 0.25 cm (Skaggs et al. 2012).

The crop data used in DRAINMOD was the crop rooting depth for sugarcane, which was estimated based on the work of several researchers (Battie Laclau and Laclau 2009; Gayle et al. 1985; Smith et al. 2005) and adjusted to suit GuySuCo's crop calendar. The maximum root depth of 80 cm was measured in the field for a mature cane stalk. Table 1 gives the crop root depth versus time as used in DRAINMOD. The sugarcane root depths in Table 1 were established relative to the top of ridges in the field. It should be noted that a root depth of 3 cm during the fallow period from December to January was chosen so that DRAINMOD could compute evaporation during this period (Skaggs 1978).

The model performance during calibration was evaluated using the statistical indicators mean absolute error (MAE) and the Nash–Sutcliffe modeling efficiency (NSE), as detailed by Skaggs et al. (2012), for daily water table depths. In addition, two other statistical indicators were used: the index of agreement (IoA) and the percentage bias (PBIAS). These were computed using the following equations:

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Table 1. Crop Rooting Depth for Sugarcane Grown in Guyana

Date	Depth (cm)
January 1	3
January 28	6
February 28	12
March 30	20
April 30	38
May 31	70
June 30	80
July 31	80
August 30	80
September 30	80
October 30	80
November 30	74
December 15	40
December 31	3

$$\mathrm{MAE} = \frac{1}{n}\sum_{i=1}^{n}|P_i - O_i| \tag{2}$$

$$\mathrm{NSE} = 1.0 - \frac{\sum_{i=1}^{n}(O_i - P_i)^2}{\sum_{i=1}^{n}(O_i - \bar{O})^2} \tag{3}$$

$$\mathrm{IoA} = 1.0 - \frac{\sum_{i=1}^{n}(O_i - P_i)^2}{\sum_{i=1}^{n}(|P_i - \bar{O}| + |O_i - \bar{O}|)^2} \tag{4}$$

$$\mathrm{PBIAS} = \frac{\sum_{i=1}^{n}(O_i - P_i)}{\sum_{i=1}^{n}O_i} \tag{5}$$

where n = total number of data points; P_i = simulated or predicted value; and O_i = observed or measured value for the MAE (Willmott et al. 2012), NSE (Nash and Sutcliffe 1970), IoA (Willmott 1981), and PBIAS (Moriasi et al. 2009) equations. Mean absolute error was used as an absolute measure given in the unit of the values, and the latter three equations were used as relative measures. Legates and McCabe (1999) recommended the use of at least one absolute and one relative measure for evaluating model performances. Skaggs et al. (2012) gave threshold values of MAE and NSE for classifying agreement between predicted and measured water table depth when evaluating DRAINMOD: MAE(cm) < 20 is acceptable, MAE < 15 is good, and MAE < 10 is excellent; NSE > 0.4 is acceptable, NSE > 0.6 is good, and NSE > 0.75 is excellent. In assessing the PBIAS, Moriasi et al. (2009) stated that PBIAS < 10% is very good, 10% < PBIAS < 15% is good, 15% < PBIAS < 25% is satisfactory, and PBIAS > 25% is unsatisfactory. The IoA ranges from 0 to 1.0, with a higher value indicating better agreement between predicted and observed values (Legates and McCabe 1999).

Simulations Using Long-Term Climate Data

Historical climate data from the Georgetown Botanical Gardens meteorological station were used for simulating the long-term hydrology of the field with the calibrated model. This station was chosen because it had the longest period of continuous climate data available (from 1974 to 2012), and it was relatively close in proximity to the field site (8.5 km). Quality assurance and quality control (QA/QC) of the climate datasets were assessed using double mass curve analysis (Allen 1996) between the two stations at Georgetown and the field site. The 39 years of daily precipitation, minimum temperature ($T_{\min}$), and maximum temperature ($T_{\max}$) were then prepared and used as input to DRAINMOD.

Additionally, the drainage discharges from the simulations were used to compute the drainage rates for five periods of duration (1-day, 2-day, ..., 5-day). The total drainage volume was taken as the combined subsurface drainage and surface runoff components from the DRAINMOD output file. These simulated drainage rates were then fitted to the Extreme Value Type I (EVI) or Gumbel distribution (Chow et al. 1988) to determine their frequency of occurrence.

Results and Discussion

Soil Analysis

Measured and computed soil properties from in situ and laboratory tests are summarized in Table 2. The upper three layers were classified as Clay according to their particle size distribution (PSD) under the USDA soil textural classification system. The clay fraction of the first three layers exceeded 60% and the remainder was composed predominantly of silt and traces of sand. The plasticity index (I_P) of the upper three layers indicated their highly plastic nature, which is characteristic of heavy montmorillonitic clay soils. These clays tend to swell significantly upon wetting and have a very low hydraulic conductivity. This is one reason why tile drains are not as effective as open ditches for drainage in heavy clay soils.

The bulk density (BD) for Layer 3 was unusually low compared with Layers 1 and 2, but their PSD values were very similar. This may be attributed to errors introduced while obtaining the samples from the field for the BD tests. Therefore, only Layer 2 was used to determine the adjusted constant for the K_{sat} estimation function

Table 2. Summary of the Measured Soil Properties for the Whitaker Series—37

Layer	Depth (cm)	Particle size distribution (%) ($n = 3$)			USDA texture	Atterberg limits (%) ($n = 3$)			Bulk density ($\mathrm{g\,cm^{-3}}$) ($n = 3$)	Particle specific gravity ($n = 1$)	Saturated hydraulic conductivity ($\mathrm{cm\,h^{-1}}$)
		Clay	Silt	Sand		W_L[a]	W_P[b]	I_P[c]			
1	0–22	63 (5.2)	35 (4.8)	2	Clay	88 (8.5)	41 (7.6)	47	1.23 (7.3)	2.69	0.99[d]
2	22–65	65 (7.7)	32 (13.4)	3	Clay	90 (12.5)	43 (6.9)	47	1.29 (4.3)	2.71	0.54 (27.7)
3	65–100	66 (7.7)	32 (16.2)	2	Clay	71 (2.3)	38 (8.2)	33	0.94 (4.1)	2.70	0.33 (21.2)
4	100–141	45 (40.2)	45 (32.4)	10	Silty clay	67 (30.3)	44 (16.6)	23	1.11 (2.7)	2.74	4.10[d]

Note: The Atterberg limit values reported are given in volumetric water content; values in brackets are the coefficient of variation (%) for measured values only.
[a]Liquid limit.
[b]Plastic limit.
[c]Plasticity index.
[d]Calculated based on particle size and bulk density using Eq. (1).

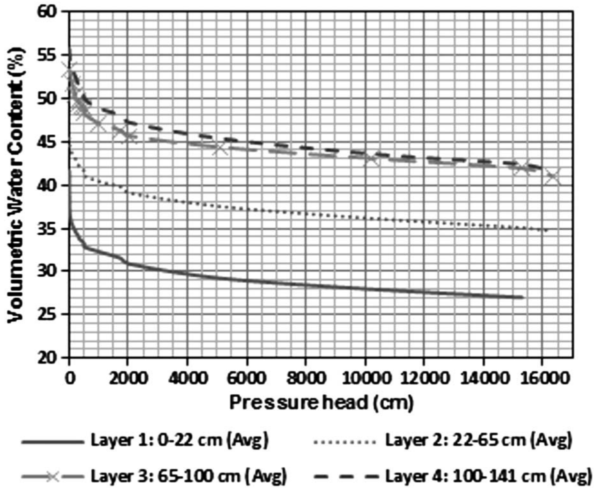

Fig. 2. Soil water characteristic curves for each soil layer of the Whitaker Series—37 (number of samples $n = 6$)

[Eq. (1)], because the equation is very sensitive to BD. Additionally, only the calculated K_{sat} values for Layers 1 and 4 were adjusted during the calibration of DRAINMOD.

The SWCC are given in Fig. 2 and are based on field averages for each soil layer. These curves were consistent with generic soil water retention curves for typical clay soils. The volumetric moisture content ranged from 56 to 27% over the applied pressure of 0–15,296 cm (0–1,500 kPa) for all four soil layers. Fig. 2 shows a trend where the moisture retention values for each layer increase as depth increases. This may be a result of variations in the microporosity of the layers due to their mineralogy.

Meteorological Characteristics

The reliability of the hydrometeorological parameters measured was assessed according to Allen (1996). Firstly, the solar radiation (Rs) data set was evaluated by using daily clear sky comparisons for computed shortwave radiation (Rso). Monthly averages of measured Rs were also compared to estimated Rs using the temperature-based model described in Allen (1996). The results (not presented) showed that the daily measured Rs followed the calculated clear sky envelope. Furthermore, the monthly averages of Rs measured versus Rs estimated showed good correlation, with a coefficient of determination (R^2) value of 0.73. Secondly, the wind speed (U) data set was assessed by comparing the measured data to that from GuySuCo's weather station at LBI (3.5 km north of the experimental site). A mass balance of the cumulative wind run for these two stations showed a very good agreement in trends, with an R^2 value of 0.99. Additionally, a double mass curve analysis (not presented) of the weekly wind speed also gave an R^2 value of 0.99. Thus the QA/QC of the measured meteorological data sets indicated that all sensors were well calibrated and in good working order.

The recorded hydrometeorological parameters at the weather station on the experimental site from March 16 to November 26, 2013 are given in Table 3 and are the average values for each month, with the exception of precipitation, which is given as the monthly total. Crop ET computed for the study period is also listed in Table 3 as monthly totals. The results show that the maximum monthly precipitation was recorded for June and July during the study period, which coincides with the seasonal long wet period for coastal areas in Guyana. Crop ET was highest for September and October, as expected for the seasonal long dry period.

Model Calibration

DRAINMOD was calibrated using water table data collected during the study period. The calibrated parameters are summarized in Table 4. Following the approach by He et al. (2002), the drainage system was first calibrated for drain spacing and depth by trial and error to minimize the MAE between observed and predicted water table depths. In the absence of an actual tile drain, an initial estimate of the drain depth was made using the average depth of the internal field drain (40 cm). No other aspect of this field drain was considered in the model, because DRAINMOD was developed for parallel tile drains. An initial estimate for the drain spacing was used from the expected range of calibrated drain spacing (5–200 m) as recommended by Skaggs et al. (2012). The drainable porosity for soil Layer 3 was calibrated using observed water table depths and the soil-water characteristics of that layer following He et al. (2002). The saturated hydraulic conductivity for soil Layers 1 and 4 were also adjusted during calibration. Lastly, the monthly ET factors were adjusted to improve the NSE between the observed and predicted water table depths during calibration. The calibration start date was set to February 1, 2013 but the model evaluation was done with the output beginning at April 1, 2013. This allowed for a two-month warm-up period, as recommended by Daggupati et al. (2015). The warm-up period was necessary because DRAINMOD was found to be sensitive to the initial water table depth, which introduces bias into the model (Malone et al. 2015). Model performance was improved at the initial stages after the warm-up period was introduced.

Table 3. Summary of the Measured Meteorological Variables at Field CM 57

Month	Precipitation[a] (mm)	Temperature[b] (°C)		Relative humidity[b] (%)		Wind speed[b] ($m\,s^{-1}$)	Solar radiation[b] ($W\,m^{-2}$)	ET_c[a] (mm)
		Minimum	Maximum	Minimum	Maximum			
March[c]	55.3	24.5	30.5	66.7	93.7	2.0	224.9	80.4
April	110.0	24.6	30.8	69.0	93.8	1.6	209.5	139.6
May	285.2	24.2	30.8	73.3	97.7	1.1	190.3	126.9
June	343.6	24.2	31.3	71.8	98.0	0.9	217.9	136.9
July	343.6	23.3	32.0	67.8	98.9	0.6	225.4	149.1
August	249.8	23.5	32.5	65.3	99.2	0.5	229.6	161.0
September	101.8	24.0	33.3	62.6	94.1	0.8	237.9	166.5
October	87.4	24.5	33.0	62.9	92.6	1.1	220.5	164.4
November[c]	131.4	23.8	32.1	65.9	94.3	1.1	188.4	116.4

[a]Monthly total.
[b]Monthly average.
[c]Data set does not cover the entire month.

Table 4. Calibrated Parameters for DRAINMOD

Parameter	Calibrated value
Drainage system	
Depth of drain from soil surface, B (cm)	70
Spacing between drains, L (cm)	1,500
Distance to impermeable layer, H (cm)	160
Soil	
Drainable porosity, M (Layer 3) ($\mathrm{cm\,cm^{-1}}$)	0.599–0.038
Saturated hydraulic conductivity, K_s (Layer 4) ($\mathrm{cm\,h^{-1}}$)	1.6
K_s (Layer 1) ($\mathrm{cm\,h^{-1}}$)	0.51
Weather: monthly ET factors	
January	1.15
February	1.01
March	1.05
April	1.06
May	1.07
June	1.13
July	0.96
August	1.02
September	0.90
October	0.80
November	0.79
December	0.75

The calibrated model was evaluated using the statistical indicators recommended by Skaggs et al. (2012), resulting in an MAE of 16.5 cm (acceptable), NSE of 0.72 (good), PBIAS of 1.0% (very good), and an IoA of 0.92 (excellent). Secondly, a comparison of the predicted and observed water table depths over the study period is shown in Fig. 3. As indicated by the model statistics, the predicted values are in good agreement with observed values spanning both wet (high water table) and dry (low water table) hydrological conditions in the field. The discrepancies between predicted and observed water table depths shown during the month of August in 2013 can be attributed to the backwater conditions observed in the internal field drain. Under these conditions, the hydraulic gradient in the field is reduced and the water table is restricted from lowering as it normally would under free drainage. This explains why the observed water tables are generally higher than those predicted during that month, because DRAINMOD cannot model backwater conditions. However, Fig. 3 clearly shows that the calibrated model was still able to capture the general trend (peaks and troughs) and response of water table depths to precipitation.

Long-Term Simulations of Field Hydrology

Historical (1974–2012) precipitation and temperature data from the Georgetown meteorological station were used as input for the long-term simulations using the calibrated DRAINMOD model. The QA/QC assessment of the climate data sets between the Georgetown and field-site weather stations indicated excellent correlations in trends. Double mass curve analysis (plots not presented) showed R^2 values of 1.0 and 0.99 for $T_{\min}$ and $T_{\max}$, respectively. Additionally, coefficient of variation (CV, %) values were 4.2 and 4.3 for daily $T_{\min}$, and 2.7 and 4.2 for daily $T_{\max}$ between the two stations. Double mass curves for daily and monthly precipitation between the two stations were also plotted (not presented). The R^2 values for both plots were 0.99, indicating a high correlation in the trends for precipitation at the two stations. These statistics, and the fact that the stations were within acceptable proximity (8.5 km) in a region with the same topography and climate, justifies the use of Georgetown's temperature and precipitation data sets for the long-term simulations with DRAINMOD.

An analysis of the historical record for the period showed that 2008 was the wettest year, with an annual precipitation of 3,365 mm; 2001 was the driest year, with an annual precipitation of 1,592 mm; and the overall average annual precipitation was 2,296 mm (±467 mm). Lastly, the daily temperature recorded for the period ranged from an average $T_{\max}$ of 30.2°C (±0.5°C) to an average $T_{\min}$ of 24.1°C (±0.4°C).

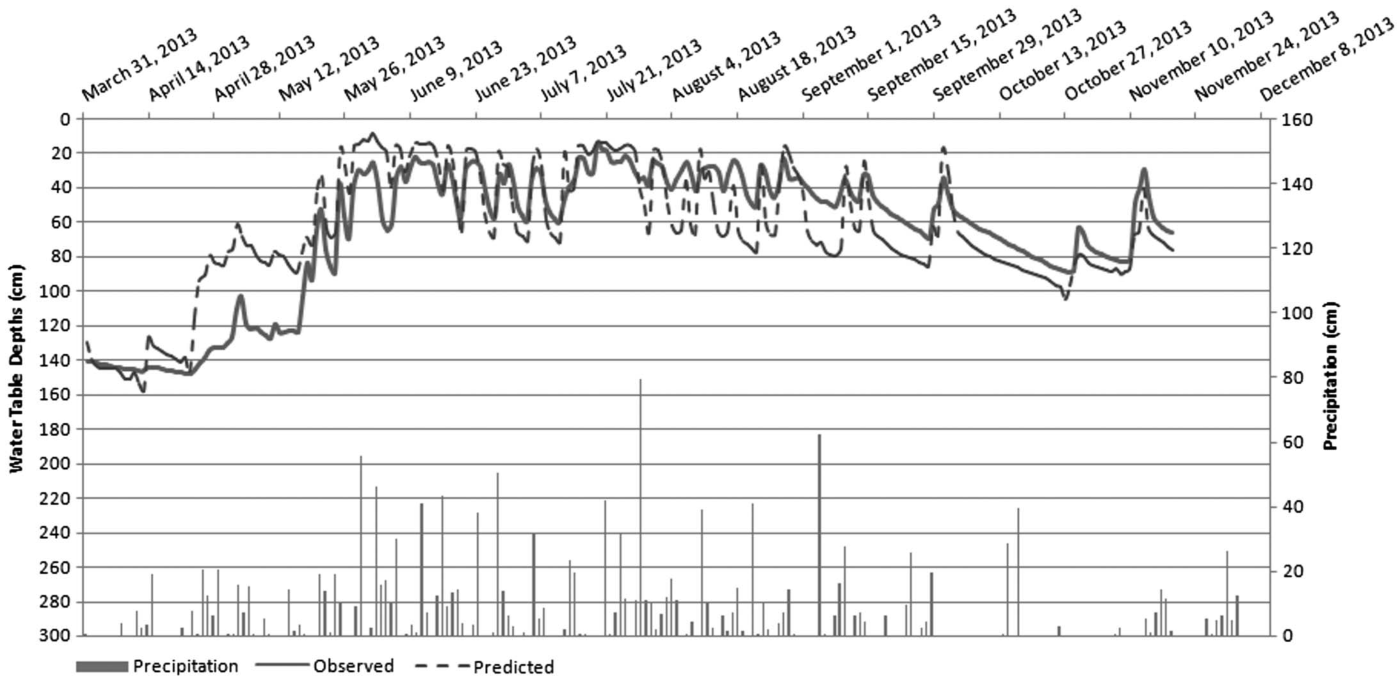

Fig. 3. Comparison of predicted and observed daily water table depths on the field for the model calibration: April 1–November 19, 2013

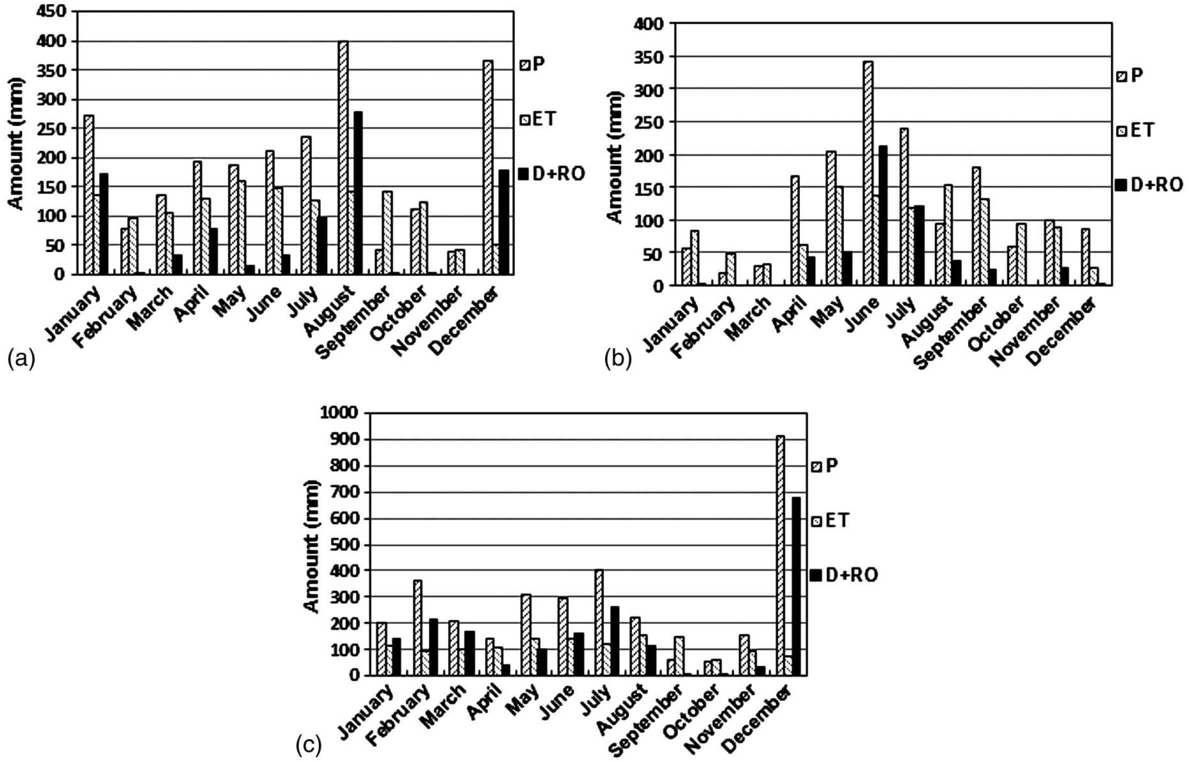

Fig. 4. Simulated monthly water balance for (a) average year (1999); (b) dry year (2001); (c) wet year (2008) (note: P = precipitation; ET = evapotranspiration; $D + \mathrm{RO}$ = total field discharge)

The primary outputs from the simulations were the ET, subsurface drainage (D), and surface runoff (RO). The latter two were combined and used to compute the total field discharge ($D + \mathrm{RO}$) on a daily, monthly, and annual timescale for the simulation period. With an annual timescale, the results showed that 2008 (the wettest year) had the maximum $D + \mathrm{RO}$ (1,917 mm), 1985 had the minimum $D + \mathrm{RO}$ (509 mm), and the overall average $D + \mathrm{RO}$ for the period was 1,023 mm (± 40 mm). The annual maximum ET occurred in 2011 (1,428 mm), the minimum ET in 1997 (1,045 mm), and the average ET was 1273 (± 101 mm) over the period.

Simulated monthly water balances for the average (1999), dry (2001), and wet (2008) years are presented in Figs. 4(a–c), respectively. The year 1999 was chosen to represent the average hydrological year because its seasonal and annual precipitation closely approximated the average values from the historical record. Monthly ET represented a significant component of the water balance for the greater part of the average and wet years because soil moisture was not limited under those climatic conditions. This was also confirmed in the long wet season of the dry year, which showed higher monthly ET values compared with the rest of the year.

The water balance for the average year [Fig. 4(a)] showed that peak $D + \mathrm{RO}$ occurred at the end of the long wet season in August, followed by the short wet season months of January and December. The dry year [Fig. 4(b)] experienced peak discharges in the middle of the long wet season (June–July) and was relatively dry for the rest of the year. In comparison, the wet year [Fig. 4(c)] experienced discharges in excess of 100 mm for eight months, with a peak of 680 mm in December. These results showed that discharge was generated in all three climatic conditions. In contrast, the wet year experienced a long dry season between September and November with very little to no discharge. This demonstrates the need for careful planning and management of the water resources along the coastal region of Guyana.

Similarly, daily water table depths simulated for the average year [Fig. 5(a)], the dry year [Fig. 5(b)], and the wet year [Fig. 5(c)] are also presented. Fig. 5(a) shows that the water table depth in the average year (1999) fluctuated between a depth of 20–80 cm from the soil surface for most of the year. However, the water table depth dropped below 160 cm in the long dry season (September–November), which is well below the crop rooting depth. In the dry year [Fig. 5(b)] the water table depth fluctuated within the top 80 cm of the soil during the long wet season (May–July), and dropped to 200 cm for the long dry season (September–November). Interestingly, the wet year [Fig. 5(c)] also experienced a considerable drop in the water table depth to 180 cm during the long dry season (September–November). It is important to note that drainage is generated for all three climatic conditions, although the water table depths never reached the surface (except for the very end of the wet year). This is because of the montmorillonitic nature of the heavy clays, which expand rapidly upon wetting and reduce percolation to the groundwater table. Compounding this is the fact that ponding occurs once the rainfall rate exceeds the infiltration capacity of the soil, as is typically the case in tropical climates. Thus surface runoff (RO) is generated quite easily even though the water table depth may not be at the surface. Moreover, this is why surface drainage systems have been most effective in draining the coastal regions in Guyana.

Simulated Drainage Rates and Their Frequencies

The monthly water balances and the daily water table depths provided a good overview of the hydrology for sugarcane fields along Guyana's coastland. However, a better assessment of the drainage system can be made by evaluating the drainage rates using the output discharge data. Therefore the simulated field discharges ($D + \mathrm{RO}$) were used to compute average drainage rates for several

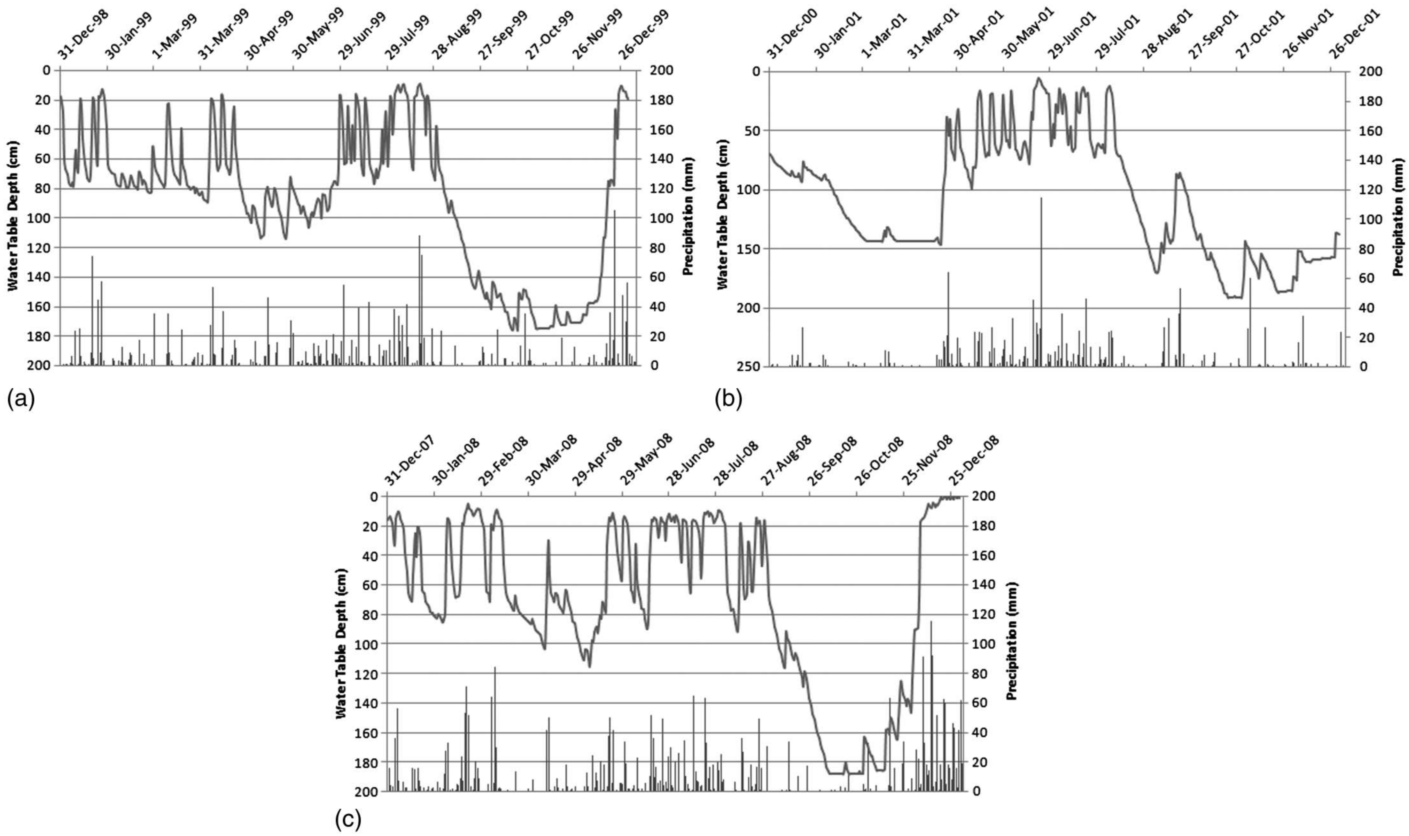

Fig. 5. Simulated daily water table depths for (a) average year (1999); (b) dry year (2001); (c) wet year (2008)

durations. The daily total field discharge was assumed to be equal to the drainage rate for a 1-day duration (DR1). The field discharges for two consecutive days were then summed and divided by two to give the average drainage rate for a 2-day duration (DR2). This pattern was repeated to find the average drainage rates for 3-day (DR3), 4-day (DR4), and 5-day (DR5) durations. Then, for each of the 39 years, the annual maximum drainage rates for each of the five durations were selected and fitted to the Gumbel distribution (EV1) for frequency analysis.

The results showed that the annual maximum drainage rates were highest for the drainage events between January 16 and 18, 2005, with drainage rates varying from 147 (DR1) to 110 mm day^{-1} (DR5). Recall that the drainage systems were traditionally planned with a design drainage coefficient (DDC) ranging from 35 to 50 mm day^{-1}, based on a 3-day storm with a 1 in 2-year return period. Hence DR3 would be the most appropriate simulated drainage rate for a direct comparison with the DDC. Therefore the results show that the annual maximum DR3 computed (125 mm day^{-1}) was more than twice the upper limit of the DDC (50 mm day^{-1}) for the aforementioned drainage event in January, 2005. However, events of such extreme nature have a low frequency of occurrence, as was shown when the data were fitted to the Gumbel distribution [Figs. 6(a and b)]. Using Fig. 6(b), the return period for the annual maximum DR3 (125 mm day^{-1}) was

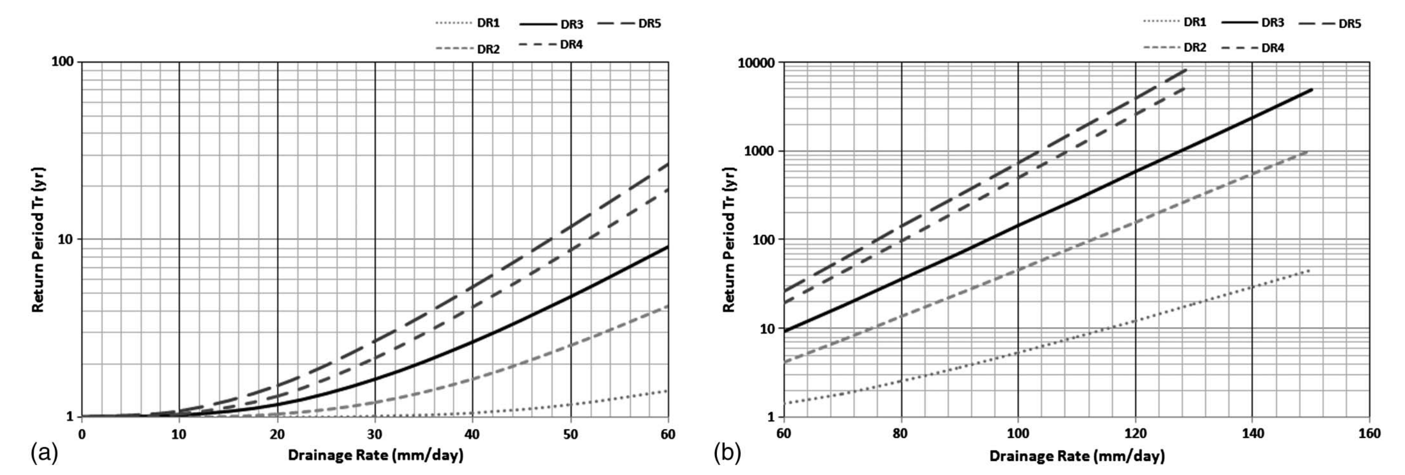

Fig. 6. Fitted EVI distributions (Gumbel) of drainage rates: (a) 0–60 mm day^{-1}; (b) 60–160 mm day^{-1} and their return periods for 1-day (DR1) to 5-day (DR5) duration events

found to be 1 in 860 years (0.116% exceedance probability). This is well outside the typical 1 in 5-year return period commonly used for agricultural drainage systems.

Alternatively, the return periods for DR3 equal to the lower and upper limits of the DDC were determined using Fig. 6(a). For the lower limit ($\mathrm{DDC} = \mathrm{DR3} = 35\ \mathrm{mm\,day^{-1}}$) the return period was 1 in 1.6 years, and for the upper limit ($\mathrm{DDC} = \mathrm{DR3} = 50\ \mathrm{mm\,day^{-1}}$) the return period was 1 in 4.8 years. Thus the simulations show that the historical design drainage coefficients used for surface drainage systems in sugarcane fields along Guyana's coastland have return periods ranging from 1 in 2 years to 1 in 5 years.

Altogether, the results from the long-term simulation of the field hydrology indicate that seasonal effects can impact agricultural crop production during all three climatic years. The water table depths fell well below the crop rooting zone during dry periods, which can limit nutrient and water uptake to crops. As previously indicated by the water balances, wet years can have deficits during dry periods, and dry years can have surpluses during the wet periods. Thus water management strategies must adequately account for these periods of excesses and shortages. The monthly water balance presented in Figs. 4(a–c) and the daily water table depth given in Figs. 5(a–c) provide valuable information for water resources planning and management in coastal areas with a humid tropical climate and heavy clays. With regard to drainage design, Figs. 6(a and b) can be used to determine either the return period for a given design drainage coefficient or the design drainage coefficient for a given return period for event durations ranging from 1 to 5 days. Future research should include additional data collection for validation of DRAINMOD and should include crop yields to evaluate the impact of water table depth and drainage on agricultural production.

Conclusions

A 4.2-ha sugarcane field at LBI sugar estate in Guyana was instrumented to measure hydrometeorological variables (precipitation, temperature, relative humidity, solar radiation, and wind speed) and water table depths to calibrate DRAINMOD for long-term simulations. DRAINMOD was calibrated by comparing observed and predicted water table depths. The calibration was done for the long wet and dry season from April to November 2013 and the model performed favorably, with an NSE of 0.72, IoA of 0.92, MAE of 16.5 cm, and PBIAS of 1.0%. Overall, the results showed that DRAINMOD can be applied to predict water table levels for sugarcane fields on Guyana's coastland.

DRAINMOD was then used with historical climate data from 1974 to 2012, to simulate the long-term field hydrology. Total field discharge was computed as a combination of subsurface drainage and surface runoff on daily, monthly, and annual timescales. The annual results showed that 2008 had the maximum total discharge (1,917 mm), 1985 had the minimum total discharge (509 mm), and the overall average for the period was 1,023 mm (± 40 mm). Simulated monthly water balances for the average (1999), dry (2001), and wet (2008) years were also presented. The results showed that discharge was generated in all three climatic conditions. In contrast, the wet year experienced a long dry season between September and November with very little to no discharge. Similarly, the daily water table depths simulated for the average, dry, and wet years were presented. The results showed that the water table depths fell well below the crop rooting zone during dry periods in all three climatic years, indicating the extent of seasonal effects on the field hydrology.

Lastly, the simulated daily field discharges were used to compute average drainage rates (DR) for five durations (1-day, 2-day, 3-day, 4-day, and 5-day). Then the annual maximum drainage rates for each of these five durations were selected and fitted to the Gumbel distribution (EV1) for frequency analysis. The annual maximum DR3 computed ($125\ \mathrm{mm\,day^{-1}}$) was found to be more than twice the upper limit of the traditional design drainage coefficient ($50\ \mathrm{mm\,day^{-1}}$). This occurred during the drainage events between January 16 and 18, 2005. However, the return period for the annual maximum DR3 ($125\ \mathrm{mm\,day^{-1}}$) was found to be 1 in 860 years (0.116% exceedance probability), which shows how extreme the event was.

Alternatively, the return periods for DR3 equal to the lower ($35\ \mathrm{mm\,day^{-1}}$) and upper ($50\ \mathrm{mm\,day^{-1}}$) limits of the historical design drainage coefficient (DDC) were determined to be 1 in 1.6 years and 1 in 4.8 years, respectively. Thus the simulations show that the DDC used for surface drainage systems in sugarcane fields along Guyana's coastland have return periods ranging from 1 in 2 years to 1 in 5 years, which are within recommended values commonly used for agricultural drainage systems.

Altogether, the results from the long-term simulation of the field hydrology indicate that seasonal effects can impact agricultural crop production during all three climatic conditions. Therefore water management strategies must adequately account for the periods of excesses and shortages. Future research should include additional data collection for further calibration and validation of DRAINMOD and should include crop yields to evaluate the impact of water table depth and drainage on agricultural production.

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