An analysis of the hydrology of a sugarcane field in Guyana

by

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ABSTRACT

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Sugarcane is one of Guyana's major agricultural crops, accounting for 3.8% of the country's gross domestic product. The crop is grown in the coastal regions with a characteristic heavy clay soil that is prone to waterlogging. The climate is wet tropical with an annual average precipitation of 2300 mm, of which almost 50% occurs during the long wet season (May-July). Together with climate change, these conditions impose the challenge of providing and maintaining an effective and efficient drainage system for water management on the sugar estates. To this end, a water balance study was conducted to analyse the performance of the existing drainage systems for a typical sugarcane field. A 4.2 ha field at La Bonne Intention was instrumented in 2013 to measure the hydrometeorological variables. In addition to the field study, DRAINMOD ver.6 was used to simulate the drainage and hydrology of the field using historical climate data.

The results of the measured field water balance for the study period (16 March to 26 November) were 170.8 cm for precipitation, 129.1 cm for crop evapotranspiration, 48.8 cm for combined sub-surface drainage + surface runoff and 2.06 cm as the net change in soil moisture. Based on the DRAINMOD simulations, the simulated drainage rate (3-day duration) for the wettest period (December 2004 to February 2005) peaked at 12 cm day^{-1}. This exceeded the upper limit of the historical design drainage coefficient of 5 cm day^{-1}. However, the return period for an event such as the wettest period, was 52 years as determined using Gumbel Type 1 distribution. Typically, drainage systems for agricultural lands are designed for a 1 in 5 yr design storm (1-day event occurring once every five years), and in conclusion from the DRAINMOD simulations, the design drainage coefficient are adequate for surface drainage systems for sugarcane fields in Guyana.

RÉSUMÉ

Maîtrise en science Naresh Gaj Génie des bioressource

La canne à sucre est l'une des plus importantes cultures de la Guyane, représentant 3.8 % du produit intérieur brut du pays. La canne à sucre est cultivée dans les zones côtières, régions caractérisées par des sols très argileux à haut risque d'engorgement autant que par un climat tropical humide avec une précipitation annuelle de 2300 mm, dont la moitié tombe au cours de la longue saison pluvieuse entre les mois de mai et de juillet. Vu ces conditions, autant que les changements climatiques, l'établissement de systèmes de drainage efficaces et efficients sur les plantations de canne à sucre pose un défi important. Cette étude utilise donc un modèle de bilan hydrique pour analyser la performance des systèmes de drainage préexistants dans les champs de canne à sucre typique. Un champ de 4.2 ha à la bonne intention a été instrumenté en 2013 pour mesurer les variables hydrométéorologiques. En plus de l'étude sur le champ, le modèle DRAINMOD (version 6) a été utilisé pour simuler le drainage et l'hydrologie du champ à l'aide de données climatiques historiques.

Les résultats du bilan d'eau pour la période de l'étude (du 16 mars au 26 novembre) donnèrent 170,8 cm pour la précipitation, 129,1 cm pour l'évapotranspiration des cultures, 48,8 cm pour le ruissellement de surface et le drainage souterrain, et 2,06 cm pour le changement net en humidité du sol. Basé sur les simulations DRAINMOD, le taux de drainage simulé (période de 3 jours) pour la période la plus humide (de décembre 2004 à février 2005) culminât à une valeur de 12 cm jour^{-1}. Cette valeur excédât la limite supérieure historique du coefficient de calcul de drainage (5 cm jour^{-1}). Cependant, la période de retour pour un événement tel que la période la plus humide était de 52 ans (calculée selon la distribution de Gumbel de type 1). Généralement, les systèmes de drainage des champs agricoles sont conçus pour des tempêtes de période de retour 1 dans 5 ans (événement 1-jour survenant une fois tous les cinq ans). En conclusion des simulations de DRAINMOD, le coefficient de drainage de conception sont adéquates pour le systèmes de drainage de surface pour les champs de canne à sucre en Guyane.

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LIST OF ABBREVIATIONS

%: Percent

°C: Degrees Celsius

AOGCM: Atmosphere-Ocean General Circulation Model

ASCE: American Society of Civil Engineers

ASTM: American Society for Testing and Materials

AWC: Available Water Content

CARICOM: Caribbean Community

CO_2: Carbon Dioxide

DC: Drainage Coefficient

DR: Drainage Rate

EDWC: East Demerara Water Conservancy

EF: Nash-Sutcliffe Model Efficiency

ET_a: Actual Evapotranspiration

ET_o: Reference Evapotranspiration

ET_c: Crop Evapotranspiration

FAO: Food and Agricultural Organisation of the United Nations

FAO-56 PM: FAO Penman Monteith (Irrigation and Drainage Paper No. 56)

GARU: GuySuCo Agricultural Research Unit

GD: Georgetown Datum

GDP: Gross Domestic Product

GuySuCo: Guyana Sugar Corporation

ha: hectares

HDPE: High Density Polyethylene

HydroMet: Hydro-Meteorological Service (Guyana)

ICID: International Commission on Irrigation and Drainage

IoA: Index of Agreement

IPCC: Intergovernmental Panel on Climate Change

ITCZ: Inter Tropical Zone of Convergence

IWRM: Integrated Water Resource Management

K_c: Crop coefficient

K_{sat}: Saturated hydraulic conductivity

LBI: La Bonne Intention

MAE: Mean Absolute Error

NAREI: National Agricultural Research and Extension Institute

PBIAS: Percentage Bias

PET: Potential Evapotranspiration

PVC: Polyvinyl chloride

RH: Relative Humidity

SPAC: Soil-Plant-Atmosphere-Continuum

SWCC: Soil Water Characteristic Curve

UG: University of Guyana

USGS: United States Geological Survey

UTM: Universal Transverse Mercator

V: Volts

W: Watts

WGS84: World Geodetic System (1984)

WTD: Water Table Depth

WUE: Water Use Efficiency

CHAPTER 1.0 INTRODUCTION

Guyana is the only English speaking country on the South American mainland and is located between latitudes 1° to 9° North and longitudes 56° to 62° West (see Figure 1). It has an area of approximately 214, 970 Km^2 of which approximately 77.2% is covered by pristine rainforest (World Bank, 2011). The country is divided into five major physiographic regions, namely: the coastal lowlands, the interior plains, the western highlands, the southern uplands and the southwest savannah (USACE, 1998). The population of the country was estimated at 800, 000 (UN Population Division, 2013) with approximately 90% of the inhabitants living along the coastal lowlands which stretches for about 459 km along the Atlantic Ocean (Beaie, 2007). It should be noted that the coastland is the smallest physiographic region (accounting for less than 5% of the country's total land area) with a width varying from 26 km in the east to 77 km in the west (Lakhan, 1994). The topography of this region is generally flat and the soil type consists of predominantly heavy clays that is prone to waterlogging (NCC, 2002).

The general climate in the coastal region is wet tropical with an annual average precipitation of 2300 mm of which almost 50% occurs during the long wet season (May-July). This presents a unique case for water management since virtually all of the country's agriculture is done on the rich alluvial soils of the coastal lowlands. Traditional agricultural crops such as rice and sugarcane depend on intricate drainage and irrigation schemes consisting of conservancies and canals. The conservancies were formed by small earthen dams that trap surface runoff from upland creeks for irrigation supplies during periods of droughts. The earthen canals were built to convey the irrigation supplies and/or for gravity drainage that allowed for the removal of excess water in a timely manner. The situation is exacerbated by the fact that the region is approximately 0.5 to 1.0 m below the mean high water level (Dalrymple & Pulwarty, 2006) and hence the daily semi-diurnal tidal cycles experienced along the coastline significantly impede drainage resulting in coastal flooding.

Figure 1.1: Location Map of Guyana showing the coastal lowlands, modified from (CIA, 2013)

While rice is more tolerant to submerged conditions, sugarcane yields can be significantly reduced under waterlogged conditions. Also the saturated heavy clays presents a further challenge for trafficability and can set back the vital land preparation works needed on the various sugarcane plantations along the Guyana coastline. The need for an effective and efficient drainage system was demonstrated in the recent 2005 and 2006 floods that resulted from prolonged periods of intense rainfall (UNDAC, 2005). Conservancies were filled beyond their maximum storage levels threatening the stability of the earthen dams and some localized overtopping compounded the already inundated coasts. The gravity drainage systems were found to be grossly inadequate for such an extreme event and several mechanical pumps had to be deployed along critical areas for relief. Some researchers are of the view that rising sea levels and mud shoal migration may effectively reduce the drainage period from conventional gravity drainage systems (Dalrymple & Pulwarty, 2006; Gratiot, 2011).

Historically, the drainage systems for these sugarcane plantations were designed as surface drains with a design drainage coefficient ranging from 35 to 50 mm/day. 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 may not necesssarily reflect the the effects of changes in rainfall intensity due to climate change, and therefore there is an urgent need to update these design drainage coefficients. Also, while some water balance studies by private engineering firms may have been carried out for some of the conservancies in Guyana, little or no work has been done to accurately measure the components of the water balance in a hydrology study at the field scale level for agricultural lands. Hence, this study is the first of this nature that aims to fill the gap in existing literature on water balance studies for agricultural lands in Guyana and in particular, sugarcane.

1.1 Objectives

The main objectives for this research were:

1) To perform a field scale hydrological water balance study on a 4.2 ha sugarcane (Saccharum Officinarum) field in Guyana;
2) To calibrate and validate DRAINMOD for simulation of the drainage and hydrology of sugarcane fields in Guyana;
3) To simulate hydrological water balances with DRAINMOD using long term climate data;
4) To assess the adequacy of the historical drainage coefficient used for the design of surface drainage systems.

1.2 Scope

The research was carried out on a 4.2 ha empoldered sugarcane field at La Bonne Intention, Guyana. While all data collected and used to calibrate and validate the DRAINMOD model are limited to this field site, the soil, topography and climate for Guyana's coastal plains are generally similar and the model can be rendered applicable for this region.

1.3 Thesis Outline

This thesis has been organised and written in the form of chapters to address the objectives previously stated. A review of the literature was done with a focus on the water management and agriculture of sugarcane in Guyana; components of a water balance; and hydrologic models for agricultural land drainage (Chapter 2). A detailed methodology for the data collection and analyses used in this study was given in Chapter 3. The results were presented and discussed in Chapter 4, and the conclusions drawn were given in Chapter 5 .

CHAPTER 2.0 LITERATURE REVIEW

2.1 Guyana's climate and water resources

Much of the work on classifying and analysing Guyana's climate was done in the late 1900's (Persaud, 1974; Potter, 1970; Ramraj, 1996) although data collection of some parameters date back to the 1880's (Mott MacDonald *et al.*, 2004). However, a study was recently done to analyse the climatic patterns in the Guianas (a geological area on the northeast coast of South America between the Amazon basin in Brazil and the Orinoco basin in Venezuela, inclusive of Guyana) with respect to regional variability in precipitation and temperature (Bovolo *et al.*, 2012). Available data for the region was deemed inadequate due to the poor spatial coverage of meteorological stations as well as discontinuities in records, especially during holidays. Thus, the authors applied retrospective analysis using the ERA-40 to generate complete data sets for the study.

The results from this research showed that the coastal areas of Guyana can be classified as wet tropical (Ar) with a bimodal precipitation distribution. This is caused by the movement of the Inter Tropical Zone of Convergence (ITCZ) over the region twice annually resulting in two dry and two wet seasons and is consistent with the results of the earlier works from the late 1900's as previously cited. Potter (1970) analysed 100 years of rainfall data from the Botanical Gardens in Georgetown and found that the primary wet season occurs from May to July, the primary dry season from August to November, the secondary wet season from December to January and the secondary dry season from February to April. Almost 50% of the average annual rainfall (2300 mm) occurred during the primary wet season while 22% occurred within the secondary wet season. In comparison, Bovolo *et al.* (2012) reported a primary dry season from September to October and a secondary dry season from February to March implying longer temporal spans for both of the wet seasons. Very little variation exists for temperature fluctuations on the coast as Ramraj (1996) reported an annual mean temperature of 27°C while Bovolo *et al.* (2012) gave a range of 25°C to 27°C from their analysis. Mott MacDonald *et al.* (2004) reported the annual mean of other meteorological variables such as: relative humidity (76.8%), sunshine hours (6.8 hrs day^{-1}) and wind speed

(2.0 m s^{-1}). Additionally, reference evapotranspiration was calculated using these data and the FAO PM-56 equation resulting with an annual mean of 4.05 mm day^{-1} and an annual total of 1475 mm for Georgetown.

Guyana was ranked as the third water resource richest country by Davie (2008) according to its annual internal renewable water resources per capita (231.7 $x10^3$ m^3/yr). The country has numerous rivers and streams that drain the upper highlands and dense rainforest towards the Atlantic coast. Notably, the three main rivers are the Essequibo, Demerara and Berbice Rivers for which the three main counties were derived from. Other important rivers along the coast that drain towards the ocean are the: Pomeroon, Supenaam, Mahaica, Mahaicony, Abary, Canje and Corentyne Rivers. Categorically, the water resources may be classified as surface water and ground water with the former originating from the many rivers and streams while the latter is stored in a coastal aquifer system. On the coastal lowlands the surface water in the form of runoff is trapped and stored by a system of small earthen dams between rivers and creeks forming shallow reservoirs or conservancies. The stored water in the conservancies would then be available as irrigation supplies for use whenever there are deficits during the dry seasons or periods of drought. In addition, the conservancies along with the sea defence and the network of drainage canals and sluices provide for flood control and mitigation during the wet seasons when there are surpluses.

The main conservancies are the Boerasirie Conservancy in Region 3 and the East Demerara Water Conservancy (EDWC) in Region 4. The Boerasirie Conservancy chiefly discharge floods into the Essequibo River via the Bonasika River. Additionally, a small discharge is released into the Demerara River. The EDWC discharge floods in both the Demerara and the Mahaica Rivers. Table 2.1 summarises the main features of these two conservancies. Other drainage and irrigation schemes along the coastal plains worth noting are: the Tapakuma Conservancy with a service area of 169 km^2 (Region 2), the Mahaica/Mahaicony/Abary Conservancy with a service area of 510 km^2 (Region 5) and the Black Bush Polders with a service area of 305 km^2 (Region 6) which was supplied with water from the Canje River via several pumping stations (World Bank, 1987). The Canje River was found to be inadequate for the irrigation demand of the region and the Torani Canal was built to augment the supplies with withdrawal from the Berbice River. The canal was built to cover 15 km in length with a design flow of 19 m^3 s^{-1} and with gated control structures at both ends connecting to two rivers. The agricultural areas for crops served with irrigation from the Canje River were given as: 28,359 ha (Rice), 21,343 ha (Sugar) and 15, 675 ha for other crops (Mott MacDonald *et al.*, 2004).

Table 2.1: Summary of the main features for the two major conservancies on Guyana's coastland.

Item	Component	Unit	Conservancy			
			Boerasirie (Region #3)		EDWC (Region #4)	
Characteristics	Catchment Area	km^2	436.0		582	
	Storage	Mm^3	220.9		144.1	
	Spill level	m GD[a]	18.68		17.53	
	Stream Slope	%	0.023		0.061	
Crops	Rice	ha	8,650		2,502	
	Sugar	ha	10,542		13,048	
	Other	ha	7,840		2,324	
Relief Structures	Discharge Capacity	$m^3 s^{-1}$	56	Warima Sluice	80	Land of Canaan Sluice
		$m^3 s^{-1}$	430	8000 ft weir	50	Maduni Sluice
		$m^3 s^{-1}$	18	Naamryck Sluice	46	Lama Sluice (Big)
		$m^3 s^{-1}$	18	Potosi Sluice	25	Lama Sluice (Small)

[a] GD represents the local reference level called Georgetown Datum

In addition to the four relief structures for the EDWC as given in Table 2.1, the Cunha and Kofi Sluices (non-functional) once provided relief via discharge to the Demerara River. Rehabilitation works were planned for the recommissioning of these structures. Also, there is the northern relief channel that is being constructed and will discharge directly into the Atlantic Ocean via a 40 m spillway with the capacity of 62.1 $m^3 s^{-1}$ (CEMCO & SRKN, 2009).

Finally the USACE (1988) assessed the water resources in the country and found that 90% of the domestic water demand was met by groundwater aquifers and the remaining amount from surface water supplied by conservancies. The major use of surface water was for the agricultural sector in which priority was given to irrigation and transportation demands before supplying the domestic needs. The UN-Water Country Brief gave a total water withdrawal at 1,444 million m^3 of which the agricultural sector accounted for 94.4% (FAO-AQUASTAT, 2013).

2.2 Agriculture on Guyana's coastland

Extensive agriculture is done on the coastal lowlands with the agricultural sector currently contributing to 20% (8 yrs average commencing from 2006) of the country's gross domestic product (GDP). There has been a steady decline however as the sector contributed to about 24% of the GDP in 2006 (BoS, 2013) and traditionally as high as 39% in 1963 (Ford, 1992). Nevertheless this sector remains important to the economy as the traditional crops (sugarcane and rice) provide employment for a significant section of the labour force. Sugarcane in particular was estimated to contribute 3.8% of the GDP in 2013 accounting for almost 22% of the agricultural sector.

In terms of sugar production, the country produced 251,643.3 tonnes as an annual average between 1990 to 2013 (BoS, 2011; GuySuCo, 2007b; A. K. Singh, 2013). Figure 2.1 illustrates the annual production for sugar during this period with a fluctuating but increasing trend up to 2004. The significant drop in 2005 was attributed to poor drainage conditions as a result of a major flood event that affected the coastal lowlands. The most recent production in 2013 fell below the average by 25.8% with a total of 186,607 tonnes of sugar produced. Authorities gave bad weather (and as a result poor drainage) conditions and labour shortages as the main reasons for this decline.

Contrasting to the decline of sugarcane production was the general increase in annual rice production after the 2005 flood event as shown in Figure 2.1 and which corroborates with rice being more tolerant to waterlogged soil conditions. The annual average production for rice during this period was 308,983.2 tonnes. The highest production of rice ever recorded in Guyana's history was achieved in 2013 with a total of 535,555 tonnes representing a 73.33% above average production. With respect to sugarcane yields for the same period, an average of 69.5 t ha^{-1} was reported by the FAO with a range of 89.1 - 56.3 t ha^{-1} (FAOSTAT, 2013). Similarly for rice paddy production during the same period, average yields of 4 t ha^{-1} was reported with the range of 3 - 5 t ha^{-1} (BoS, 2011; GRDB, 2007; A. K. Singh, 2013).

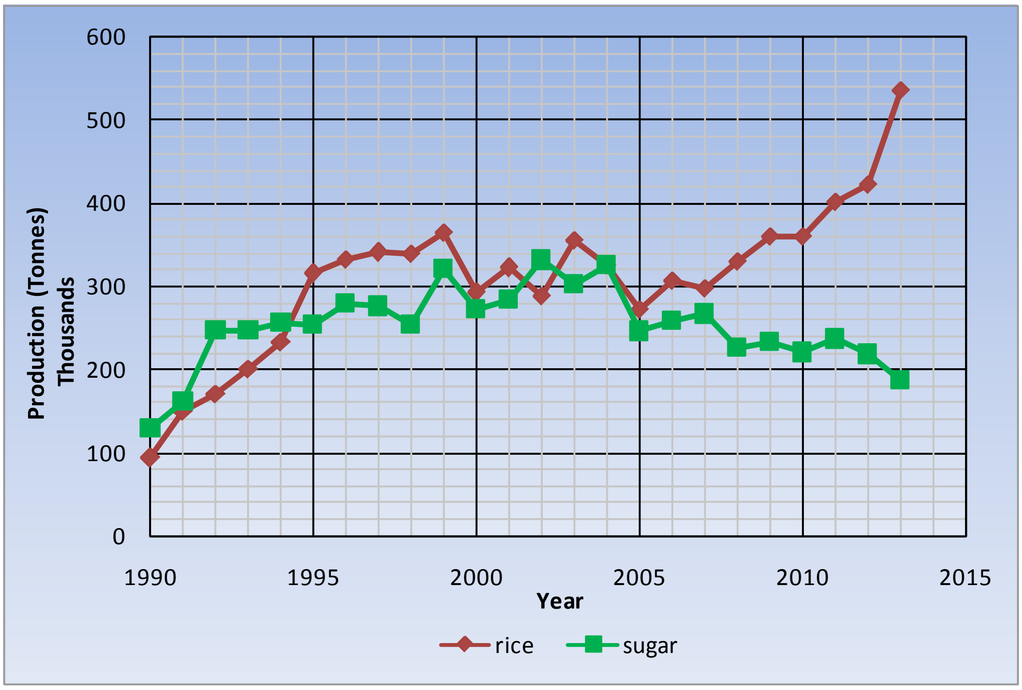


Figure 2.1: Annual Production for Sugar and Rice in Guyana for the period 1990 to 2013.

Non-traditional crops such as coconuts, vegetables and fruits, along with livestock rearing (cattle, poultry, swine and sheep) are also part of the agricultural sector for the coastal region (Homenauth, 2007). The non-traditional crops altogether was estimated to contribute 2.5% of the GDP in 2013 while the corresponding estimate for livestock was given as 2.7% (BoS, 2013).

2.2.1 Brief history of sugar production

Historically, sugar cultivation was first introduced into Guyana in the 1630's by the Dutch settlers. With the coastal lowlands being 0.5 to 1.0 m below the mean sea level (NCC, 2002), the Dutch setters employed an intricate empoldering system of dams and canals to reclaim the fertile alluvial soils. In addition, they built a sea defence system of walls to keep the high tides at bay and sluices (kokers) to evacuate the excess runoff from land drainage via gravity outflow. This system proved to be very effective at that time, but with global sea level rise and mud shoal migrations along the coast (Gratiot, 2011) pumping has supplemented gravity drainage if not entirely replacing it in some locations. By the 1800's, under rule of the British agricultural development expanded along the coast with sugarcane plantations in the counties of Demerara and Berbice. However, Lakhan (1994) notes that the transition from Dutch to British did not bring about any major change in land reclamation of the coastal zone and in fact the British continued on the drainage systems originally built by the Dutch. Further, by the early 1920's Guyana became a major rice producer after East Indian indentureship ended and water management therefore became a critical issue. However, the first Drainage and Irrigation Board was created until 1941 (Lakhan, 1994).

Sugarcane was planted on large estates with a series of rectangular field blocks bounded by irrigation and drainage canals. Several factories were located on the sugar estates which processed the sugarcane into sugar for commercial and local markets. These assets were largely owned by a private British conglomerate (Booker Brothers and McConnell & Co., Ltd) until 1976 when they were nationalized and merged with the two Demerara Sugar Company estates to form the Guyana Sugar Corporation (GuySuCo) which was then controlled by the State.

Currently eight estates exist, four in the county of Demerara and four in the county of Berbice with a main sugar terminal for bulk export located in Georgetown. The four Demerara estates are: Uitvlugt, Wales, La Bonne Intention and Enmore. The four Berbice estates are Rose Hall, Albion, Skeldon and Blairmont. Figure 2.2 shows the spatial distribution of these estates along the coastal region. Also, it is worth noting that the Berbice estates are considered as the eastern estates while the Demerara estates are considered as the western estates.

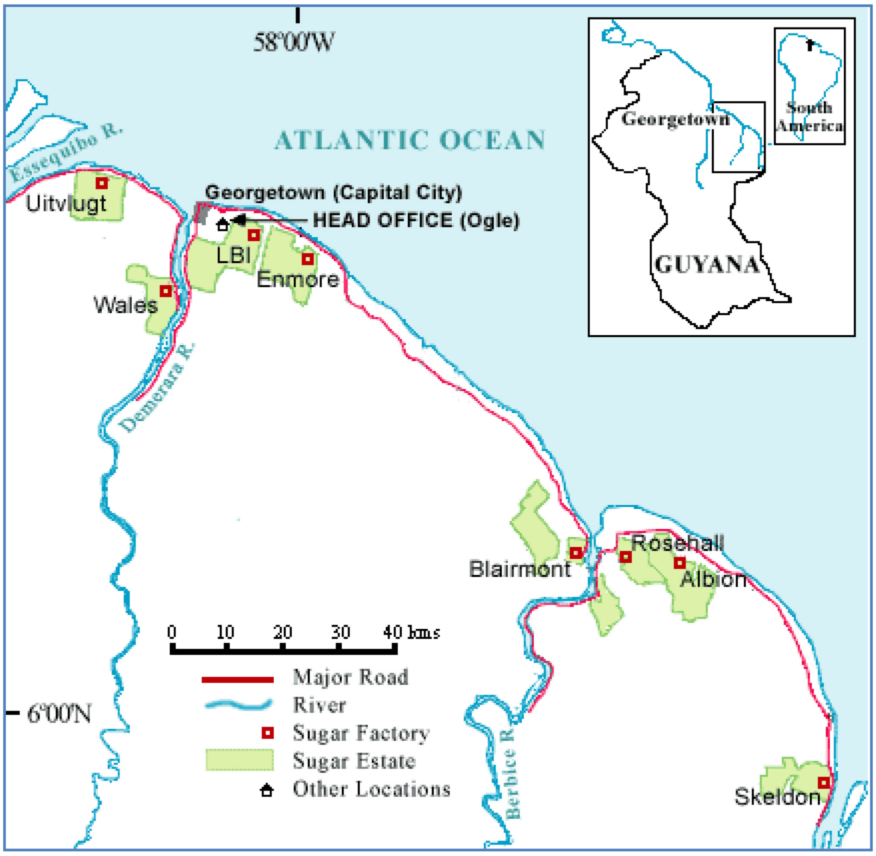


Figure 2.2: Location of the sugar estates on the coastal lowlands of Guyana (GuySuCo, 2007a).

2.3 Water management for agriculture

Water is perhaps one of the most important natural resource available on earth that is required for human sustainability. The management of this resource can be seen as "the activities necessary to balance supplies and demands of water" (Lehr *et al.*, 2005) and it includes the economic, social, political and environmental considerations in the decision making process (Linsley *et al.*, 1992). As such, the involvement of the different sectors associated (both directly and indirectly) to the water resources of a community has led to a more integrated decision - making management process. This approach has been referred to as Integrated Water Resource Management (IWRM) and was formally conceptualized by the International Conference on Water and the Environment in Dublin, Ireland (Davie, 2008).

The agriculture sector, through food production, has been attributed as the largest user of water globally with estimates at around 70% (Biswas *et al.*, 2009). It is therefore imperative that efficient water management practices be exercised in all agricultural related activities. Central to this objective is the application of drainage and irrigation principles to water management systems for agriculture with the aim of eliminating or reducing water related factors that limit crop production (Skaggs, 1980). The benefits of such systems are apparent as seen in the increase of crop yields, better trafficability and the reduction of nutrient losses from the soil (with controlled drainage). One key aspect of the water management systems used on agricultural farmlands is the control of the ground water table and hence the common terminology of water table management is often used in the given literature. Effective management tools such as DRAINMOD (section 2.6.2), are thus used to predict water table level or depth under varying climatological, crop and soil conditions for a given water management system.

2.3.1 Global water management practices for sugarcane cultivation

Water table management practice for sugarcane cultivation varies across the globe with the main criteria being local climate, topography and soil conditions. In the United States of America, the water management systems on sugarcane fields within the sub-tropical climate varies from sub-surface tile drains in the Lower Mississippi Valley, Louisiana to open surface ditches in the Everglades, Florida. The tile drains and control sumps have been successfully applied to control the water table level for drainage and sub-irrigation in the silt loam soils of Louisiana (Carter *et al.*, 1988) resulting in significant increases to sugarcane yields. In the Everglades wetland, seepage based controls through open drainage/irrigation ditches were used to manage soil-water in the highly organic muck soils (Kwon *et al.*, 2010; Omary & Izuno, 1995). Also, about 10% of the sugarcane produced in South Florida was grown on high water table sandy soils; thus irrigation became the driving factor for water table management as Obreza *et al* (1998) showed in their experiment as they established 0.6 m as the optimum depth of the water table to maximise sugarcane yields. In contrast, Wiedenfeld (2004) conducted field experiments in semi-arid Texas to evaluate drip irrigation systems on sugarcane fields against the traditional furrow irrigation.

In India and Pakistan, sugarcane was planted and grown in the semi-arid and sub-tropical areas with soil types ranging from silt loam to sandy loam soils. Hence, the focus was on irrigation to meet the consumptive use of the sugarcane crop with approximately 89% of 4.0 million ha under irrigation management (P. N. Singh *et al.*, 2007). Traditionally, surface irrigation systems were employed as described by P.N. Singh & Mohan (1994) and Subramanian *et al* (1991) with aims of increasing sugarcane yields. However, Ramesh *et a*l (1994) showed that drip irrigation systems can save up to 44% on water consumption against surface irrigation. The surface irrigation/drainage networks across the region consisted mainly of ditches and furrows.

In Australia, shallow water tables along the coastline in tropical and sub-tropical climates were common for areas under sugarcane cultivation (Hurst *et al.*, 2004). The drainage systems on these sugarcane plantations consisted mainly of surface ditches and mole drains which drain directly into a system of canals. These canals or open surface channels were either drained by gravity or pumping or a combination of both depending on the tidal influence on the outlet conditions (Yang, 2008). Irrigation was also an important part of the water management system in Australia's sugarcane industry as 60% of the crop produced required some form of irrigation (Inman-Bamber & Smith, 2005).

Brazil was reported as the largest producer of sugarcane in the world accounting for approximately 25% of the world's sugar production (Lee, 2013) with about 9.5 million hectares of land under cultivation in 2009 (Cabral *et al.*, 2012). Most of the sugarcane was grown under rainfed conditions in the southern regions of the country where the climate was tropical wet and humid and hence there was little need for irrigation at that time (Garoma *et al.*, 2012). However, irrigation was necessary in the northern regions and is ever increasing due to the expansion of sugarcane production in low rainfall areas to meet the demand for biofuel (Cabral *et al.*, 2012). The soil type in these regions were typically sandy clays and the topography was often undulating hills resulting in deep water tables (often >1 m below the ground surface) and good drainage conditions. Hence the practice of water table management was virtually impractical and water management systems were based on irrigation scheduling with overhead sprinklers such as the centre pivot system (V. P. R. Silva *et al.*, 2012).

2.3.2 Water management practices for sugarcane cultivation in Guyana

In Guyana, sugarcane is planted along the coastal plains which is bordered by the Atlantic Ocean in the north . The climate along the coast is tropical wet and humid, with the soil type ranging from heavy clays to organic peats (pegasse). These conditions result in waterlogged soils with a shallow water table and thus emphasis on drainage is key to the water management system on the sugarcane plantations/estates. A network of field ditches and drainage canals with polders delineate the sugarcane fields in rectangular blocks along the coastal flatlands. The Boerasirie Conservancy and the EDWC provide a consistent supply of water through open channels (canals) fed by gravity flow with gated structures for the Demerara estates as needed (USACE, 1998). The estates located in the East Berbice region receive water from the Canje Creek and Torani Canal via a combination of gated structures and mechanical pumps. These water management schemes are in most part operated and maintained by the local sugar authority (GuySuCo).

Drainage

Drainage is achieved by gravity flow through canals towards the nearest river or ocean via outlet structures (sluices). The sluices are equipped with control gates that opened during the low tides. A typical tidal curve is shown in Figure 2.3 for Port Georgetown. Guyana's coastland experiences a semi-diurnal tide and hence there are two high tides and low tides daily. The average land elevation at Georgetown is 0.5 - 1.0 m below the mean high water level of 17.2 m GD and most agricultural areas along the coast have an average land elevation of less than 16.0 m GD. The average sill level (elevation of sluice floor) of most sluices are set at 14.0 m GD. Thus, the tidal influence is a significant deterrent to gravity drainage as the lowest tide is about 0.5 m above the average sill level. As a result, mechanical pumps are used as a supplement and in some cases solely to evacuate excess runoff. In addition, sea level rise and unpredictable mud shoal movement further exacerbate the drainage situation by decreasing the head difference at the sluices.

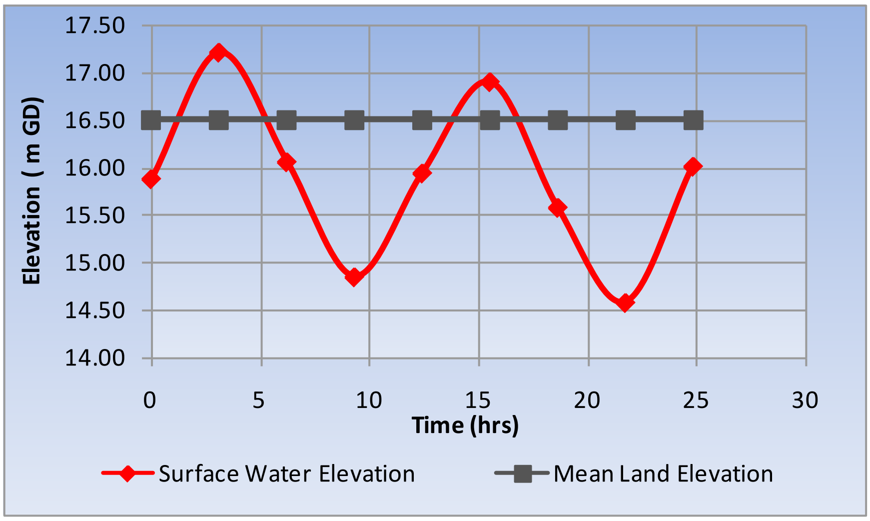


Figure 2.3: Typical tidal curve for Georgetown showing the two high and low tides for a 24 hr period (MARAD, 2008). Note the mean land elevation (16.5 m GD) limits the water depth in drainage canals and hence a short period exits for free discharge

Historically, the drainage systems have been designed for drainage coefficients (DC) of 35.6 mm day^{-1} in the dryer estates, east of the Berbice River, and 45.7 mm day^{-1} in the wetter estates, west of the Demerara River. 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). In comparison, a 2004 study done by Mott MacDonald Ltd. of the UK to assess the hydrology and water resources of Guyana, computed a design drainage coefficient of 40.0 - 56.0 mm day^{-1} westerly across the coastal region, for an equivalent 3-day storm at 50% non-exceedance (return period of 2 years) using the Gumbel distribution (Mott MacDonald *et al.*, 2004). However, the major flood events in 2005 and 2006 could not be accounted for in the recent study of 2004 and hence a new assessment of an adequate drainage coefficient is needed.

Irrigation

In contrast to drainage, irrigation for sugarcane is rarely needed and the water requirement is most often met by rainfall. However, the estates east of the Berbice River are relatively drier and seasonal irrigation is practiced. This is done by flooding the fields on a block basis or several blocks with either mechanical pumps or by gravity flow via a cut in the irrigation canal dam. The decision to irrigate is based on soil moisture deficit calculations, where 127 mm (5 inches) below field capacity was set as the maximum deficit threshold to commence irrigation.

In addition, water is used in a canal system for the transportation of harvested sugarcane stalks to the factories via steel barges (punts). The water levels in these navigational canals are maintained at a critical level for two reasons. Firstly, the sugarcane laden punts must have sufficient water depth available to allow for free navigation from the fields to the factories. Secondly, the stability of the adjacent transport dams can be significantly reduced if the water levels drop below the critical stage. As such, the maximum free board in the navigational canals was set as 250 mm (Eastwood, 2009).

Recirculation pumping has been practiced on some estates in the past, and it was encouraged for periods of drought or intense rainfall conditions. This involved pumping water from the main drainage systems to the irrigation/navigation canals. Further, a practice called "flood fallow" is often employed prior to land preparation works on sugarcane fields. This entails inundating the fields for a period of approximately 6 months and has the direct benefits of improving soil structure and nutrient content as well as controlling against pests (such as castniomera licus) and diseases (Eastwood, 2009).

It is worth mentioning that water is also needed for the factory operations of converting cane into sugar, but quantifying this was beyond the scope of this research. Furthermore, data on the quantity of water actually used for irrigation and navigation supplies for all estates at any given time period was practically non-existent. However, Mott MacDonald *et al.* (2004) estimated the annual field irrigation demands for sugarcane based on annual rainfall exceedance probabilities and found the following for 90% Non-exceedance: 8.3 L s^{-1} ha^{-1} (Region 3), 10.5 L s^{-1} ha^{-1} (Region 4), 11.7 L s^{-1} ha^{-1} (Region 6).

2.4 Water balances

The water balance of a system is an important concept to water management as it forms the very core of hydrology as a science. In its simplest form it entails accounting for the total water input and output of the system with a net gain or loss in storage. The water balance equation is a mathematical description of the hydrological processes operating within a given timeframe and it is based on the principle of the conservation of mass and energy (Davie, 2008). As such, it has many applications in the study of hydrology and water resources management, and more specifically in the area of drainage and irrigation design for agricultural engineering. The equation in its generic form is as follows (Raghunath, 2006):

$$\text{Inflow} = \text{Outflow} \pm \Delta W \qquad (2.1)$$

where: ΔW is the change in water storage. This equation forms the basis of several computational models (see section 2.6.2. on DRAINMOD) used for water table management studies. There may be more than one source of inflow as well as multiple types of outflow in a given system. These components are discussed in further details in the following section (2.4.1.) of this chapter.

Water balances are performed on different systems to define and establish the distribution and movement of water. With respect to agriculture, water requirements of crops is based on energy exchanges at the cropped surface and the internal energy gradients in the soil-plant-atmosphere-continuum (SPAC). The water retained by crops are many times less than the total water transpired through the crop's stomata and from the soil surface, often combined as evapotranspiration (Inman-Bamber & Smith, 2005). Water balances are often used to determine the amount of water used by crops through actual evapotranspiration (ET_a). The estimate of the consumptive use of water by crops is essential for the efficient design of irrigation schedules and general water management practices.

2.4.1 Components of a water balance

The components of the water balance equation are based on the application of the equation to a specific set of field conditions. In its general form, the components are usually subdivisions of the main inputs and outputs of the system. Inflows may be in the form of precipitation or irrigation. Outflows can occur through evaporation and/or transpiration and surface runoff. Studies done by Ghiberto *et al.* (2011) and Silva *et al.* (2012) on soil-water balances of sugarcane crops in Brazil utilised the following components in the water balance equation at the soil-plant-atmosphere-continuum:

$$P + I - D + CR - ET_a - R \pm \Delta S = 0 \qquad (2.2)$$

where: P is the precipitation; I is the irrigation; D is the internal drainage; CR is the capillary rise in the root zone; ET_a is the actual evapotranspiration of the crop; R is the surface runoff and ΔS is the change in soil moisture (net increases are added while net decreases are subtracted). Both of these studies used the soil-water balance equations to solve for the actual evapotranspiration of the sugarcane crop as an unknown. Evett *et al.* (2011) also used a form of the water balance equation with similar components to determine actual evapotranspiration and to compare soil-water sensing probes such as neutron and electromagnetic probes. Interestingly, the study done by Silva *et al*. (2012) compared the performance of the single and dual crop coefficient of sugarcane grown in a tropical region using the FAO-56 methodology. Further discussions on crop coefficients for sugarcane are included in section 2.4.3. of this chapter.

2.4.2 Evapotranspiration and ET models

The processes of evaporation and transpiration are commonly joined together and considered as evapotranspiration in the study of hydrology. Hoffman *et al.* (1990) stated that "ET represents the total water lost by a cropped surface through the conversion of liquid water to a gas". It is relatively difficult to differentiate between the two in most field conditions (Wilson, 1990). As such, accurate field measurements (using lysimeters) are cumbersome and tedious and estimates are often computed using empirical relationships that are established from sound scientific principles. These range from the oldest method of determining evaporation using evaporation pans (Linsley *et al.*, 1992) to the more contemporary methods of estimating potential evapotranspiration using radiation and temperature based models. Current studies have been focusing on the development of artificial neural network (ANN) modelling computation techniques (Trajkovic, 2005; Zanetti *et al.*, 2007) and gene-expression programming (GEP) (Traore & Guven, 2011) for modelling reference evapotranspiration using minimal weather data. Additionally, work was also done by Chabot *et al.*, 2002 and Chabot *et al.*, 2005 to determine actual transpiration of the sugarcane crop using sap flow measurements.

According to Hoffman *et al.* (1990) through Penman (1948), potential evapotranspiration (ET_p) quantifies the evaporative demand of the atmosphere based on the transpiration of a "short, green crop" completely covering the ground and never short of water. It was further stated that reference evapotranspiration (ET_o) was the actual water loss by a specific crop covering the soil surface with unlimited soil water supply and the most common reference crops being short grass and alfalfa. Actual ET was then estimated by the use of crop coefficients for a specific crop during its growth stages.

Evapotranspiration estimates can be classified into four major groups (Hoffman *et al.*, 1990): evaporation pan methods, temperature methods (empirical), radiation methods (energy balance) and combination methods. ET models derived from these groups require a collection of meteorological parameters such as temperature, relative humidity, solar radiation and wind speed as common inputs. Numerous studies have been carried out by researchers in all parts of the world to compare, calibrate and evaluate ET models for site specific locations.

Temperature and Combination Models

Temesgen *et al.* (2005) used data from 37 stations in a network of weather stations from the California Irrigation Management Information System (CIMIS) and compared four reference evapotranspiration (ET_o) equations using simple linear regressions. The results showed that of the four equations used (CIMIS Penman equation, FAO-56 Penman Monteith, ASCE Penman Monteith and the Hargreaves equation), the CIMIS Penman correlated well with the FAO-56 and ASCE PM equations. Also the Hargreaves equation compared well to the FAO-56 PM equation.

Furthermore, studies by Trajkovic (2005) used four temperature based approaches [radial basis function (RBF) network, Thornthwaite, Hargreaves and reduced set Penman Monteith methods] for estimating reference evapotranspiration in Serbia. These were compared to the FAO-56 PM method and it was found that the RBF network was better in predicting ET_o than the remaining calibrated temperature based models. In addition, Trajkovic (2007) went a step further and calibrated the exponent parameter of the Hargreaves equation to get a better agreement with the FAO-56 PM equation under humid conditions. The results from this study showed that the calibrated Hargreaves model overestimated the FAO-56 PM model by approximately 1% and hence supported the use of a calibrated Hargreaves model in a humid region where only temperature data is available.

The FAO-56 PM equation (Allen *et al.*, 1998) is a combination model and has been accepted by researchers globally to give accurate ET_o estimates and was given as:

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma\frac{900}{T+273}U_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34U_2)} \qquad (2.3)$$

where ET_o is the reference evapotranspiration (mm day^{-1}), R_n is the net radiation at the crop surface (MJ m^{-2} day^{-1}), G is the soil heat flux density (MJ m^{-2} day^{-1}), T is the mean daily air temperature at 2 m height (°C), U_2 is the wind speed at 2 m height (m s^{-1}), e_s is the saturation vapour pressure (kPa), e_a is the actual vapour pressure (kPa), Δ is the slope of the vapour pressure curve (kPa °C^{-1}) and γ is the psychrometric constant (kPa °C^{-1}).

Temperature and Radiation Models

Lu *et al.* (2005) compared six potential evapotranspiration methods in the south eastern United States with actual evapotranspiration computed from the water balances of forested watersheds. Three of the methods were temperature based (Thornthwaite, Hamon and

Hargreaves-Samani) and the remaining three were radiation based (Turc, Makkink and Priestly-Taylor). The study showed that the ET_p values computed from the six methods correlated highly with the actual ET estimates.

Solar radiation data are rarely available for long term climatic analyses and hence the temperature based ET model developed by Thornthwaite (1948) is commonly used to determine potential evapotranspiration. The general Thornthwaite equation as used in DRAINMOD (Skaggs, 1980) for computing potential ET was given as:

$$e_j = cT_j^a \tag{2.4}$$

where e_j is the potential ET for month j and T_j is the monthly mean temperature (°C), c and *a* are constants which depends on location and temperatures as calculated from the annual heat index "I".

In the absence of missing weather data such as wind speed, solar radiation and relative humidity, Allen *et al*. (1998) suggested the use of the Hargreaves model which utilises daily minimum and maximum air temperatures. He recommended local calibration by using the FAO-56 PM model and regression analysis. Work done by Trajkovic (2007) as previously discussed showed that good correlation between Hargreaves and FAO-56 PM can be achieved in humid regions by calibrating the exponent parameter in the standard Hargreaves equation which was given as:

$$ET_{oH} = 0.0023\, R_a\, (T_{max} - T_{min})^{0.5} \left(\frac{T_{max} + T_{min}}{2} + 17.8\right) \tag{2.5}$$

where ET_{oH} is the Hargreaves reference evapotranspiration (mm day^{-1}), R_a is the extraterrestrial radiation (mm day^{-1}), T_{max} and T_{min} are the daily maximum and minimum temperatures respectively (°C) and 0.0023, 0.5 and 17.8 are the Hargreaves coefficient, exponent and temperature coefficient respectively.

Evaporation Pan Models

Lastly, Allen *et al*. (1998) and Hoffman *et al*. (1990) states that the daily evaporation readings from a Class "A" pan often serves as a good estimate for local ET values and should be used to compare with the ET_o computed from the empirical models. Empirically derived pan coefficients K_p for local areas are used to compensate for the differences resulting from the loss of water between a water surface and a cropped surface. The sugar estates in Guyana are equipped with Class A pans and records of daily measurements are kept. However, these estates do not apply a pan coefficient to its readings for correction. They utilise a factor called the crop canopy coefficient (F) which converts the pan readings directly to crop ET or crop consumptive use based on the respective growth stage of the crop. The values of F for plant and ratoon sugarcanes along with the procedure for use were given in Guysuco's Agriculture Operations Guidelines (Eastwood, 2009). The general crop consumptive use or ET_c model was given as:

$$ET_c = E_{pan} \times F \tag{2.6}$$

where ET_c is the crop evapotranspiration (mm day^{-1}), E_{pan} is the daily pan evaporation reading (mm day^{-1}) and F is the crop canopy coefficient (dimensionless). Table 2.2 gives the values of F at different stages of the sugarcane growth and development stage as used by the local agronomists.

Table 2.2: Crop Canopy Coefficients at different development stages for a sugarcane crop.

Crop Development Stage	**Crop Age (Weeks)**		**Crop Canopy Coefficient (F)**
Sugar Cane	Plants	Ratoons	
Up to 25% full canopy	1 - 4	1-3	0.50
25 to 50% full canopy	5 -8	4-6	0.80
50 to 75% full canopy	9-12	7-9	0.95
75 to 100% full canopy	13-16	10-12	1.10
Full canopy	17-40	13-36	1.15
Maturation	>40	>36	0.70

Adapted from: GuySuCo's Agriculture Operations Guidelines (Eastwood, 2009).

2.4.3 Consumptive water use and the sugarcane crop coefficient

The importance of estimating water use of plants or crops has already been stressed by numerous authors as it relates to computing irrigation requirements. Inman-Bamber and Smith (2005) discussed the water relations in sugarcane and its response to water deficits with the aim of strengthening the knowledge-base in the area of irrigation management. The study concluded with several recommendations for further research in areas such as: evapotranspiration over a wider range of surface conditions and physiological water stress thresholds for irrigation. An important point to note is that of biofuel production from crops such as corn and sugarcane. Cabral *et al.* (2012) conducted a study in Brazil to determine the evapotranspiration of sugarcane in order to assess the crop's water use and its effect on the regional water budget and by extension annual yields. The authors discussed the need for water management in low rainfall areas as Brazil was expanding sugarcane production for biofuel outside its traditional agricultural areas. In contrast, Guyana's sugarcane production areas were almost fully rainfed with little need for irrigation and more emphasis on drainage. However, accurate estimates on sugarcane water use are still vital for effective drainage design. Moreover, estimated ranges of precipitation in the Amazonia region, as given by the climate change scenarios (IPCC, 2007a) showed 40% decrease during the dry season and 10% decrease during the wet season by the year 2080. These extremities may trigger the need for irrigation and therefore new practices for water management can be borrowed from the examples aforementioned.

The consumptive water use is the actual or crop evapotranspiration (ET_c) of water via the crop canopy and surrounding soil surface and hence the role of ET_o is central to its determination. This is supplemented by the use of crop coefficients (K_c) representative of the different growth stages of the crop being studied. The standard procedure for determining the ET_c was outlined in the Irrigation and Drainage Paper No. 56 by the FAO (Allen *et al.*, 1998) and was given as:

$$ET_c = K_c ET_o \tag{2.7}$$

where ET_c is the crop evapotranspiration (mm day^{-1}), K_c is the dimensionless crop coefficient and ET_o is the reference evapotranspiration (mm day^{-1}).

The crop coefficient encompasses the physical and physiological characteristics of the crop at different periods in the growth stage. Allen *et al.* (1998) gave two approaches for computing ET_c, namely the single and dual crop coefficient approaches. The single K_c approach assumed that the difference in evapotranspiration between the cropped and reference surface was combined into one single coefficient. The dual K_c approach, which was developed for more precision, involved splitting the coefficient into two factors describing separately the difference in evaporation and transpiration between the cropped and reference surface. Thus, the single coefficient K_c was replaced by (Allen *et al.*, 1998):

$$K_c = K_{cb} + K_e \tag{2.8}$$

where K_{cb} is the basal crop coefficient and K_e is the soil water evaporation coefficient (all dimensionless). The parameters to determine the dual K_c and the detailed procedure to determine the daily ET_c were described in the Irrigation and Drainage Paper No. 56 by the FAO (Allen *et al.*, 1998). It included the method for the construction of a basal crop coefficient curve which allows one to determine K_{cb} values at any given time during the crop's growth stage. The soil evaporation component K_e was determined through a series of rigorous computations based on a simple water balance at the soil surface layer. Allen *et al.* (2005), gave a detailed description of the standard FAO procedure and they introduced three extensions to improve accuracy for special situations. Further, they carried out a sensitivity analysis on the depth of the evaporative layer, the fraction of the surface wetted by irrigation and the estimation of the fraction of ground cover. This indicated that these factors were moderately sensitive and not substantial for improving estimates.

With respect to crop coefficients for sugarcane, Inman-Bamber and McGlinchey (2003) compared the FAO-56 single crop coefficients to those derived from long term Bowen ratio energy balance on experimental sites in Australia and Swaziland. They reported good agreement between the two methods for the initial (0.4) and mid stages (1.25) of growth but suggested 1.25 for working out the water balance against FAO's 0.7 at the end phase. However, it was recommended to use the FAO's 0.7 at the end or mature stage of growth when scheduling irrigation so as to impose some stress in the crop which enhances the sucrose content. Figure 2.4 shows both single and dual Kc values of sugarcane with time for countries within the tropical zone.

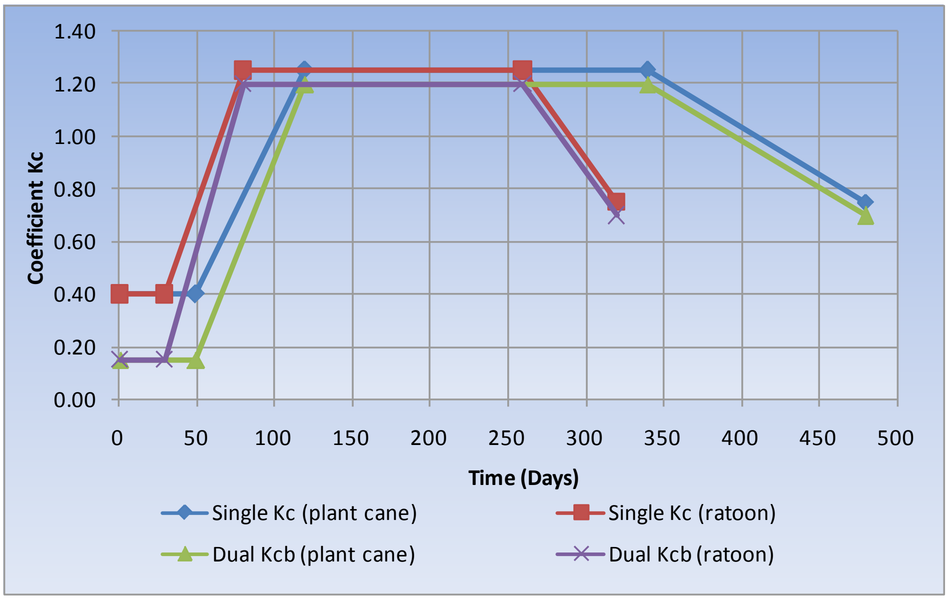


Figure 2.4: Crop Coefficient Curves for Sugarcane according to FAO (Allen *et al.*, 1998).

Fittingly, a study was done in the tropical region of Brazil to compare the use of the single vs. dual crop coefficients for sugarcane (V. P. R. Silva *et al.*, 2012). Crop ET was determined by field water balance and tested against the standard FAO-56 PM method using the single and dual K_c values. The findings showed that dual K_c values were in good agreement with the measured values as against the single K_c values which underestimated the crop ET by as much as 36%.

2.4.4 Unsaturated flow and soil moisture

Another condition for water flowing through the soil medium to be considered for any drainage analysis is that of unsaturated flow. This type of flow occurs in the zone above the phreatic surface or water table called the vadose zone. The unsaturated zone plays an important role in the plant growth with regards to water uptake by roots, evaporation from the soil and the movement of fertilisers and salts. Also, the soil moisture dynamics in the upper regions of the soil profile affects the trafficability of fields and thus it is important to understand soil-water movement in the unsaturated zone when establishing or evaluating criteria for drainage systems (Ritzema, 1994).

Darcy's law is also applicable to unsaturated flow in soils as explained by Smedema & Rycroft (1983). Szymkiewicz (2013) also discussed the application of Darcy's law through the use of Richard's equation which remains a very useful tool for unsaturated zone modelling. The moisture content at varying depths and suctions in the soil profile governs the mechanics of unsaturated flow as capillary forces and adsorption forces are dominant. Soil moisture can be measured by destructive and non-destructive methods. The gravimetric method is the most common destructive type of determining soil moisture content. Non-destructive techniques include: neutron scattering, gamma-ray attenuation, electrical resistance blocks, capacitance method and time domain reflectrometry (Davie, 2008; Ritzema, 1994). These non-destructive methods have the advantage over the destructive methods in that the moisture content at the same point can be measured on a continuous basis. However, the gravimetric method is used to calibrate these techniques and it remains a simple and reliable way to determine soil water content (Davie, 2008).

An important concept in unsaturated soil mechanics is that of soil water retention. The pressure head or soil suction of the soil water changes with changes in the water content of the soil (Ritzema, 1994). This relationship can be measured for a soil sample in a laboratory using a pressure plate apparatus and a graph describing this relationship is generated known as the soil water characteristics curve as shown in Figure 2.5 (Davie, 2008).

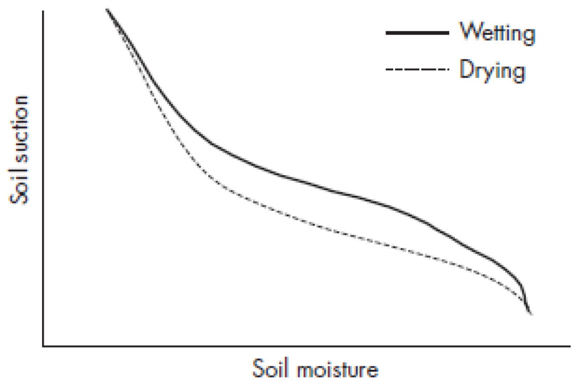


Figure 2.5: A generic plot of the soil water characteristics curve for a soil sample showing the hysteresis as a result of testing under wetting and drying conditions (Davie, 2008).

Generally, soil hydraulic properties (both in the saturated and unsaturated state) are difficult to measure due to practical and/or financial limitations. Researchers have done work to develop indirect relationships between these properties of soils and ones that are easily measured, such as: particle size distribution, bulk density and organic matter content. One such model (ROSETTA) was developed by Schaap *et al* (2001), and can be used to estimate water retention, and the saturated and unsaturated hydraulic conductivities.

The drainage simulation model, DRAINMOD, allows for the soil moisture retention characteristics among other soil properties to be used as inputs and hence the model accounts for unsaturated flows in the soil layers above the watertable. Also, when data is limited, ROSETTA can be used to estimate these properties for direct input into DRAINMOD (section 2.6.2).

2.5 Agricultural land drainage

Categorically, land drainage comprises of two main components, surface drainage and sub-surface drainage. The importance of drainage within the context of agriculture and water resources management was stressed in the previous sections of this chapter. This linkage was documented by Smedema & Rycroft (1983), who discussed the two main problems associated with poor drainage; impaired crop growth and impaired farm operations. Prior to this in 1979, the International Commission on Irrigation and Drainage (ICID) defined land drainage as "the removal of excess surface and sub-surface water from the land to enhance crop growth, including the removal of soluble salts from the soil." (Ritzema, 1994). The design of drainage systems with respect to agricultural function is usually expressed as input parameters relating physical drain dimensions and spacing to a required drainage intensity. This is done with the objective of maximising economic returns from the farm system with an optimal drainage intensity (Schilfgaarde, 1974). Thus, agricultural land drainage may be viewed as an important economic activity with direct costs associated to the drainage systems and direct benefits tied to the increase in yields as a result of improved drainage conditions (Smedema & Rycroft, 1983).

The configuration and layout of an agricultural drainage system depends on many site specific conditions or factors. Some of these include: land topography, crop type, soil type and water table depth. The system may be designed for surface drainage, sub-surface drainage or both, and it may consist of open field ditches or buried pipes that discharge into main peripheral drains which then convey the drainage water to a stream, lake, river or sea via tide gates and/or by pumping (Linsley *et al.*, 1992).

Smedema & Rycroft (1983) discussed the criteria for drainage design separately for groundwater (sub-surface) drainage and shallow surface drainage. The basic design criterion for shallow drainage systems is to remove excess water (design discharge) from the land as a result of the design rainfall or other sources (snowmelt, irrigation losses etc.) within a specified time frame. For groundwater drainage, controlling the water table during and after the occurrence of the specified design rainfall is the main design criterion.

Heavy clay soils are characterized by very low hydraulic conductivities and the use of sub-surface drainage systems may not be economical. Further, a low infiltration rate may limit the ability of water to enter the soil and result in surface ponding. Ritzema (1994) suggested a limit for the use of sub-surface drainage systems to where infiltration occurs easily during a storm lasting two or three consecutive days. If ponding occurs, the author recommended the use of surface drainage systems consisting of furrows and small ditches.

For surface drains and in the absence of water level records, the design discharge may be derived by several methods of rainfall-discharge relationships. Smedema & Rycroft (1983) described these methods under calibrated and uncalibrated rainfall-discharge relationships. The widely used Rational Formula and the Curve Number Method were listed as the preferred methods for estimating peak runoff, and subsequently the design discharge for sloping basins. For flat basins however, the design discharge can be derived through a series of rigorous calculations involving the distribution of a design storm and its corresponding discharge over small time intervals (6 hr periods) and zones of equivalent travel time within the basin.

2.5.1 Drainage theories and principles

The engineering design of drainage systems entails the application of theories on water flow both overland and through the soil pores. Established theories and principles within the fields of hydrology and hydraulics are amalgamated to quantify the input parameters necessary for computing drain size and spacing as stated earlier. Central to these is the application of Darcy's law (developed in 1856) which describes the flow of water through a porous medium. The law states that the rate at which water moves through a soil is proportional to the gradient of the soil water potential, with K_{sat} (saturated hydraulic conductivity) as the constant of proportionality in the relationship (Smedema & Rycroft, 1983). Darcy's law is applicable to horizontal and vertical flow through layered soils. However, the law is only valid for laminar flows with a Reynolds number (Re) of less than one (Ritzema, 1994). Whereas Darcy's law is applied to groundwater flows in soil, the Chezy-Manning equation is used to describe the flow of water overland and in open ditches or drainage canals. As discussed previously, flows in heavy clays are limited by the very low permeability and most often surface drains are the only practical solution for consideration. The Chezy-Manning equation is used for the hydraulic design of these surface drains.

Hooghoudt Equation

The Hooghoudt equation was developed in the Netherlands during the 1940's to determine pipe drain spacing for sub-surface drainage under steady-state conditions and was given as (Smedema & Rycroft, 1983):

$$q = \frac{8Kd_eh+4Kh^2}{L^2} \qquad (2.9)$$

where q is the drain discharge (m day^{-1}), K is the hydraulic conductivity of the soil (m day^{-1}), d_e is the equivalent depth to the impervious layer (m), h is the height of the water table relative to the water level in the drain (m) and L is the drain spacing (m). In agricultural lands with sub-surface drainage systems only, q is used directly as a drainage coefficient and once predetermined, it can be used to find the required drain spacing for pipe drains in a given set of local soil and hydrological conditions. Figure 2.6 depicts a conceptual model of flow to a vertical drain as described by Hooghoudt.

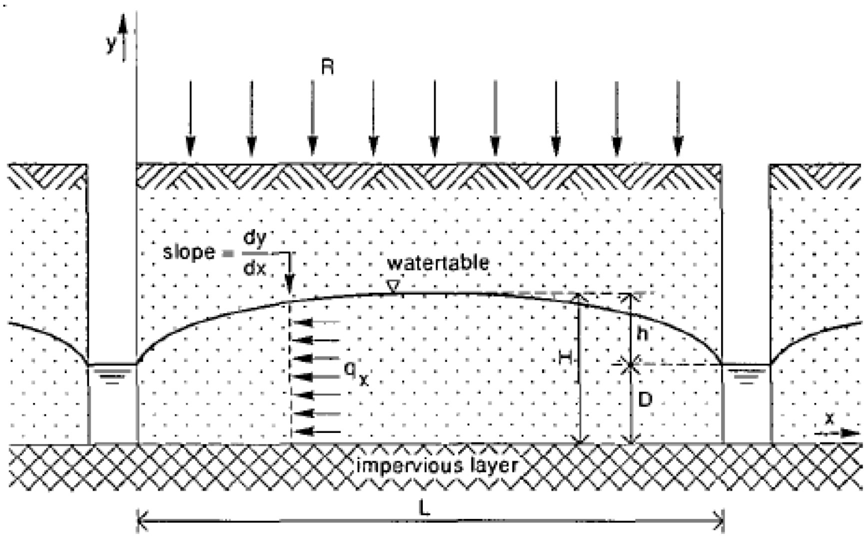


Figure 2.6: Flow to vertical drains in a homogenous soil layer bounded by an impervious layer as conceptualized by Hooghoudt (Ritzema, 1994).

Ernst Equation

In a two layer soil system, Hooghoudt's equation can only be applied if the drain level coincides with the interface of the two soil layers. Otherwise, the Ernst equation is used when the drain level is positioned at any depth of either of the soil layer. The equation splits the total head into three components of head loss, namely: vertical flow, horizontal flow and radial flow. The Ernst equation according to Ritzema (1994) was given as:

$$h = q\left(\frac{D_v}{K_v} + \frac{L^2}{8\sum(KD)_h} + \frac{L}{\pi K_r}\ln\frac{aD_r}{u}\right) \qquad (2.10)$$

where h is the total available head (m), q is the design discharge rate (m day^{-1}), D_v is the thickness of the layer in which vertical flow is considered (m), K_v is the vertical hydraulic conductivity (m day^{-1}), L is the drain spacing (m), $\sum(KD)_h$ is the transmissivity of the soil layers through which the water flows horizontally (m^2 day^{-1}), K_r is the radial hydraulic conductivity (m day^{-1}), *a* is the geometric factor of the radial resistance, D_r is the thickness of the layer in which the radial flow is considered (m) and u is the wet perimeter of the drain (m).

Both of these equations were derived from the principles of ground water flow using Darcy's law and are applicable for use in steady-state conditions. The steady-state condition implies that the flow through the soil is constant as recharge rate equals discharge rate resulting in a constant head (Smedema & Rycroft, 1983). In reality, the recharge rate to the groundwater table is transient and hence an unsteady state between the recharge and discharge rate is more common. The two main equations for unsteady flow as presented by Ritzema (1994) were the Glover-Dumm equation for a falling watertable and the De Zeeuw-Hellinga equation for a fluctuating watertable. The former is applicable to irrigated areas while the latter is used in humid areas where high intensity rainfall occurs as concentrated discrete storms.

2.5.2 Drainage coefficient as a design criterion

The design criterion for surface drainage is not as straightforward as that for groundwater or sub-surface drainage. As previously discussed, the criterion for groundwater drainage was based on controlling the watertable after a design rainstorm and the Hooghoudt (2.9) and Ernst (2.10) equations can be readily applied in such situations. For surface drainage, the criterion centres on removing excess water from overland flow (surface runoff) and/or interflow after a design rainstorm. The application of the Chezy-Manning equation in this situation is chiefly to design the hydraulic dimensions of the surface drains to take off the excess water. The criterion should therefore be based on the amount of water (excess) to be removed within a given time. This was summarised by Ritzema (1994) who stated that agricultural constraints such as a crop's sensitivity to saturated soil and ponded water should be the basis of any design criteria. Also, consideration should be given to the hydraulics of flow through channels and structures as well as the effects on the environment.

When estimating the excess water for removal by drainage systems in the context of agricultural land drainage, the general basin discharge formula as given by Smedema & Rycroft (1983) can be applied:

$$Q = \frac{q.A}{1000} \quad (2.11)$$

where Q is the basin discharge ($m^3\ s^{-1}$), A is the drainage basin area at the point considered (ha) and q is the drainage coefficient or specific/unit design discharge ($L\ s^{-1}\ ha^{-1}$). This formula however, is misleading as it implies the drainage coefficient is independent of the basin area. The effects of discharge transformation and rainfall distribution in large basins results with a decrease in q as A increases (Smedema & Rycroft, 1983). The use of the area reduction factor accounts for these effects in flat basins. One common example is the Cypress Creek Formula developed for the United States for basins <5000 ha with slopes <0.5 %. The area A in equation 2.11 is reduced by the exponent 5/6 as the reduction factor (Smedema, 1985).

Willardson (1982) discussed drainage coefficients and their development in terms of humid and arid regions. The author noted the difficulty of establishing and applying accurate values for drainage design during that period. For humid regions, experience of the local area formed the basis of the selection of a suitable drainage coefficient with values ranging from 9 to 40 mm per day. In contrast, arid areas had to be irrigated and the drainage coefficient was computed from irrigation requirements based on soil-water balance with allowance for a leaching fraction to control salinity. This resulted in values under 6 mm per day (Willardson, 1982).

Madramootoo (1999) outlined computing the drainage coefficient as an important parameter for drainage design and that it can be obtained through frequency analysis of precipitation records with a 1 in 5 year design storm being suitable for agricultural lands. A variation of the frequency analysis method for determining the drainage coefficient for bunded lands under rice cultivation was given by Smedema & Rycroft (1983). This was a graphical method where the tangent to the rainfall duration curve, from an allowable depth, was given as the drainage coefficient.

Carter (1999) also stated that the selection of a drainage coefficient was based on experience and knowledge of local crop, climate and soil conditions as the author discussed soil surface configurations for drainage designs. These views were expressed earlier by Smedema (1985) who stated that specific values for drainage coefficients can be derived from through experiences and/or empirical formulae relating drainage coefficients to land conditions and rainfall intensity. One such formula used in Florida, USA was given (Smedema, 1985) as:

$$q = 16.4 + 14.75R_e \qquad (2.12)$$

where q is the drainage coefficient (in imperial units of ft^3 s^{-1} $mile^{-2}$) and R_e is the excess rain (in imperial units of inches per day) derived from a 2 to 5 yr frequency of 24-48 hr design storm derived through the United States Department of Agriculture (USDA) curve number graph. However, these formulae are only applicable for the regions in which they were developed. In this regard, Smedema (1985) proposed the linear reservoir model to determine the drainage coefficient for heavy clays which was successfully applied to regions in the Netherlands, Croatia and Tanzania. The model was based on assessing the dynamic storage and the reaction factor. The results from this research gave drainage coefficients of: 10.1 - 13.4 mm day^{-1} (Netherlands) and 20.9 - 27.2 mm day^{-1} (Croatia) for a 1 in 3 yr design storm. Notably, the drainage coefficient for sugarcane grown on heavy clays in Tanzania was given as 64.4 - 70.5 mm day^{-1} for a 1 in 3 yr design storm.

Madramootoo (1999) gave design drainage coefficients for various site conditions and crops of which 3 mm day^{-1} was given for sugarcane grown on mineral soils in the semi-arid and arid regions of Pakistan. Ahmadi (1995) computed the drainage coefficient for humid areas in Iran using measured water table depths and field hydraulic conductivities. The author found the value to be 2.2 mm day^{-1} which was in agreement with local values used for drainage design. Also, Shrivastava and Patel (2008) designed surface drains for sugarcane planted on heavy black soils in India. They used rainfall frequency analysis to derive a drainage coefficient of 118 mm day^{-1} for a 1 in 10 year storm.

A study done by Naraine in 1990 on Guyana's sugarcane plantation, as cited by Ritzema (1994), produced the design drainage coefficient by the graphical method. This was done for a cumulative 5-day rainfall with a 10 year return period. However, the tangent to the cumulative discharge duration curve was used as the drainage coefficient in this study. The Curve Number Method was used to calculate surface runoff or discharge from the design rainfall. It must be noted that Naraine's study showed that under these conditions a drainage coefficient of 35 mm day^{-1} was optimum for a surface drainage system.

Additionally, it was established that the sugarcane yields decreased steadily as the water level in the collector drains exceeded a corresponding depth of 0.9 m below the soil surface for 7 days (number of high water days) in a season.

In section 2.3.2. it was discussed that the local sugar authority in Guyana used a drainage coefficient of 35.6 - 45.7 mm day^{-1} for the design of the drainage systems to which Naraine's value lies on the lower limit. Also, the design drainage coefficient as a result of the 2004 study done by Mott MacDonald cited values with the range of 40.0 - 56.0 mm day^{-1} based on Gumbel distribution of historical rainfall data. However, these values have not been experimentally verified with the aim of assessing its adequacy for drainage design. This is both important and critical to better manage the water resources available for agriculture, specifically within the context of climate change and the recent coastal flood events of 2005 and 2006 (Hickey & Weis, 2012).

While drainage research was primarily focused on maximising crop yields and improving trafficability to optimize economic returns, contemporary research has shifted its attention to include mitigation against environmental impacts from nutrient loads and water quality (Skaggs *et al.*, 2006). This was the rationale behind a research to develop relationships to estimate drainage intensity with maximised economic returns and reduced environmental impacts. Skaggs *et al.* (2006) conducted simulations to determine drain spacing corresponding to predicted maximum economic return for corn production in Eastern USA. They developed a regression equation to estimate the drainage coefficient in terms of seasonal precipitation for a fixed drain depth and surface depression storage. The results concluded with an optimum drainage intensity of 5.8 mm day^{-1} on average for four soil types with 16.1 mm day^{-1} as the maximum.

2.6 Drainage simulation and modelling

A model is simply a representation of an object or prototype system that exists in the physical world. Categorically, models may be broadly classified as physical models or mathematical /computational models. In scientific analyses, the choice of a specific type of model is dependent on numerous factors which are outside the scope of this review for discussion. However, with one major factor being the rapid development of computing power by digital computers, mathematical models have become a clear cut choice in virtually all the scientific disciplines (Karplus, 1983).

The modelling process can be thought of as a generic cycle which entails firstly a fair description of the prototype system, developing a conceptual model to best represent this system, formalizing a set of equations and laws as a mathematical model to describe how the system works and then implementing the mathematical laws and equations collectively as a computational model. At this stage experiments are usually carried out to verify and validate the developed computational model to that of the prototype through simulations. This process is entwined in the overall modelling process and is the key stage in evaluating models for virtually all applications.

2.6.1. Hydrologic models

Hydrologic models are continuously being developed for numerous applications in the natural sciences and engineering. According to Moriasi *et al* (2012), there was an increasing use of hydrologic and water quality models for evaluating the impacts of climate, land use and agricultural management practices on both the quantity and quality of water and land resources. In addition, these models have been successfully applied in the design of drainage and irrigation systems within the context of water management for agriculture.

A wide array of hydrologic models exists at present and the difference between any two can range from either's ability to perform its function at the field to watershed scale (spatial) or on a time scale of minutes to years (temporal). The more superior and popular models are those incorporating both extremes at the spatial and temporal scale as well as the ability to simulate multivariable processes.

Moraisi *et al* (2012) gave an excellent summary of 25 hydrologic and water quality models that are normally used by experts globally. The paper presented information on the models aimed at developing guidelines for model calibration and validation. Twenty of the 25 models were reported to simulate both hydrology and water quality (sediment, nutrients and pesticides etc.). Interestingly, DRAINMOD was the only model in the set that simulated hydrology only. Other hydrology based models that were included in the summary and of particular relevance to drainage were ADAPT, EPIC & APEX and SWAT.

ADAPT (Agricultural Drainage and Pesticide Transport) model is a field-scale water table management model developed as an extension to the GLEAMS (Groundwater Loading Effects of Agricultural Management Systems) model (Gowda *et al.*, 2012). GLEAMS was integrated with DRAINMOD to produce a model with the ability to predict both the quality and quantity of surface and sub-surface flows. The model has four components, namely: hydrology, erosion, nutrient transport and pesticide transport; and it operates on a daily time step.

EPIC (Environmental Policy Integrated Climate) and APEX (Agricultural Policy/Environmental eXtender) models were developed to evaluate problems associated with water quality, agricultural water resource and other hazardous environmental conditions (Wang *et al.*, 2012). They are both continuous models that simulate evapotranspiration, surface runoff, soil erosion etc. on a daily temporal scale. The EPIC model was limited to analyses at the field-scale level by design but the APEX extension has allowed for larger areas to be analysed up to the watershed level.

SWAT (Soil and Water Assessment Tool) was designed to assess the impact of land use and management on water, sediment and agricultural chemical yields in unmonitored watersheds (Arnold *et al.*, 2012). The model runs on a daily time step and is capable of continuous simulation over long periods of time. The major model components include: hydrology, weather, soil characteristics, plant growth, nutrients, pesticides, bacteria and pathogens and land management.

Several researches have carried out experimental work using many of these models in the array. Lebel (2011) used the SWAT model in India to assess the impacts of climate change on water management at the watershed scale, while Gollamudi (2006) applied SWAT to assess the hydrology, sediment and nutrient movement at the field scale level in Quebec, Canada. Of more relevance to this research was the study done by Qureshi and Madramootoo (2001) which used the SWAP93 (Soil Water Atmosphere Plant) model to simulate the soil-water balance of a sugarcane crop in Pakistan. They concluded that the model generally underestimated ET values by 18% and thus recommended a better ET estimation model to be used within SWAP93.

2.6.2. DRAINMOD

Brief Description and History

DRAINMOD is a field scale hydrology model that was developed for poorly or artificially drained lands (Skaggs *et al.*, 2012). The model is process-based and distributed, and it conducts water balances on either an hourly or daily time scale. It is based mainly on simple water balances in the soil profile and on the soil surface. DRAINMOD was initially developed by Skaggs (1978) at North Carolina Water Resources Research Institute. Numerous modifications to the original model have been made from its inception to present time. Some of these modifications included the introduction of salinity and nitrogen components as DRAINMOD-S and DRAINMOD-N respectively in Version 5.0 of the model during the late 1990's. More recently (Skaggs *et al.*, 2012), the model has been applied to analyse the hydrology of wetlands and forested areas resulting in DRAINMOD-Forest, as well as the biogeochemistry and plant growth for agricultural lands in DRAINMOD-Decision Support System for Agro-technology Transfer (DSSAT).

DRAINMOD predicts and simulates hydrologic conditions such as infiltration, sub-surface drainage, surface runoff, evapotranspiration, vertical and lateral seepage, water table depth and drained pore space in the soil profile. Additionally, relative crop yield, irrigation water depth applied and variables for indicating wetland hydrology status can be predicted by the model. Figure 2.7 shows the water balance components considered in the model.

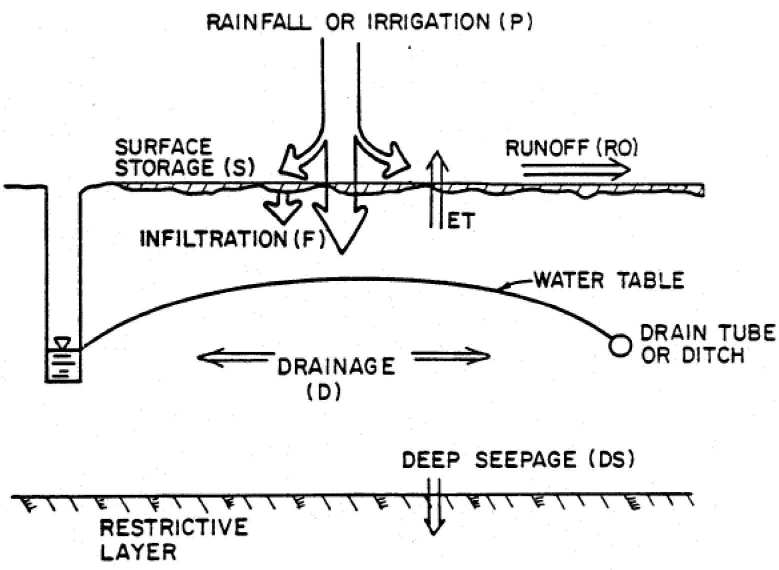


Figure 2.7: Schematic of the water balance components as part of the water management system with drainage to ditches or drain tubes as considered by DRINAMOD (Skaggs, 1980).

DRAINMOD components

As discussed in previous sections, the water balance is core to the computational construct of the model. Within the soil profile of unit surface area this balance was expressed as (Skaggs *et al.*, 2012):

$$\Delta V_a = D + ET + DLS - F \tag{2.13}$$

where ΔV_a is the change in the water-free pore space or air volume (cm), D is the drainage from (or sub-irrigation into) the section (cm), ET is the evapotranspiration (cm), DLS is deep and lateral seepage (cm) and F is infiltration (cm) entering the section in time increment Δt.

At the soil surface, the water balance was computed from (Skaggs, 1980):

$$P = F + \Delta S + RO \tag{2.14}$$

where P is the precipitation (cm), F is the infiltration (cm), ΔS is the change in volume of water stored on the surface (cm) and RO is surface runoff (cm) during time Δt.

The infiltration component in DRAINMOD was based on the Green-Ampt model (Skaggs *et al.*, 2012) and was ultimately given as:

$$f = A/F + B \tag{2.15}$$

where A (cm^2 h^{-1}) and B (cm h^{-1}) are parameters that depend on soil properties and plant factors, such as extent of cover, depth of root zone and soil water content when rainfall begins.

Sub-surface drainage was estimated with the steady-state Hooghoudt equation (Skaggs *et al.*, 2012):

$$q = 4K_e m(2d_e + m)/L^2 \tag{2.16}$$

where q is the drainage rate (cm h^{-1}), m is the midpoint water table elevation above the drain, K_e is the equivalent lateral hydraulic conductivity of the profile (cm h^{-1}), d_e is the equivalent depth from the drain to the restrictive layer (cm) and L is the drain spacing (cm).

ET was determined as a two-step process with the daily ET_p computed using Thornthwaite (1948) temperature based models (see section 2.4.2.) and then ET_a was computed based on limiting conditions of soil water availability. The reader is referred to the technical reference report by Skaggs (1980) for a detailed description and general discussion of the components of the model.

Application and Evaluation

Skaggs *et al* (2012), stated that with respect to spatial variability, DRAINMOD has been applied to the full spectrum ranging from a point on a landscape to watersheds of several thousand hectares. It is worth repeating that the model was originally developed for the field scale application on agricultural lands and that its ability to extrapolate at the spatial scale justifies its robustness and hence popularity among global experts.

Importantly, hydrological conditions on fields with single or non-parallel drains can be simulated by calibrating the effective drain spacing (L) as done by Northcott *et al* (2001), He *et al* (2002) and Amatya *et al* (2003).

Numerous studies have been conducted by researchers around the world to evaluate DRAINMOD's performance as a tool for water table management for a diverse range in climate, crop and soil conditions. The hydrologic model has been evaluated mainly by the output variables such as water table depths and drainage volumes. Skaggs (1982) and He *et al.* (2002) have conducted experiments in USA and Bourke (2011) in Canada, to evaluate DRAINMOD's performance using water table depths and have found good agreements between observed and predicted values. The average absolute deviation between observed and predicted water table levels were 8.1 cm and < 20 cm for Skaggs (1982) and He *et al.* (2002) respectively. Bourke (2011) reported on the Nash-Sutcliffe coefficients among others, for the predicted vs. observed water table levels and gave ranges of 0.23 - 0.74 under free drainage and 0.10 - 0.66 under controlled drainage. However, Sinai & Jain (2006) found that the model was not appropriate for use in the Jordon Valley, Israel with a range of 0.3 - 1.7 m of deviation between the predicted vs. observed water table levels. Three reasons were offered to justify the disagreement in water table depths observed and predicted, two of them were linked to the hydraulic boundary condition effects of the Jordon River and the other was attributed to significant deep and lateral seepage.

DRAINMOD was also evaluated using drainage volumes from corn field plots with surface and sub-surface drainage systems in Ohio, USA (Skaggs *et al.*, 1981). The results showed average deviations of 1.00 - 4.32 cm and 0.99 - 4.10 cm between observed and predicted flows for sub-surface and surface drains respectively. As an ideal scenario, the model was evaluated using both water table depths and drainage volumes in Ontario, Canada under water table management for corn production (M. Singh *et al.*, 1994). The results from this study indicated average absolute deviations between observed and predicted water table levels of 2.4 - 10 cm for conventional drainage and 8.2 - 35.3 cm for control drainage while the deviation for drainage volumes ranged from 0.28 - 0.36 mm d^{-1}.

Lastly, DRAINMOD has been successfully applied and evaluated to water table management studies for sugarcane crops in USA and Australia (Carter *et al.*, 1988; Gayle *et al.*, 1985; Yang, 2008) based on water table depth observations only. Carter *et al.* (1988) showed that with water table management in Louisiana, sugarcane yields increased by 15% while processed sugar yields went up by 22%, both with >95% confidence limits. Further, DRAINMOD was evaluated for water table level predictions on sugarcane fields under similar conditions in Louisiana by Gayle *et al.* (1985) who showed an average deviation of 3.0 - 14.4 cm between observed and predicted levels. Likewise, Yang (2008) evaluated

DRAINMOD for sugarcane fields under Australian conditions and showed that the standard error of 0.07 m was obtained between observed and predicted water table levels.

Calibration and Validation

Interestingly, the inputs for DRAINMOD may be determined independently as the model was originally developed to be used without calibration (Skaggs *et al.*, 2012). Calibration is however necessary as variability in inputs such as soil properties, crop root depths, depressional storage etc. can be significant. Additionally, this author and presumably many others, believes that because calibration is central to the simulation and modelling process, it should never be left as an option.

Table 1 of Skaggs et al (2012) efficiently summarised the input data required for calibration in DRAINMOD such as the soil's saturated hydraulic conductivity (K_{sat}) and water retentions points etc. Singh *et al* (2006) used K_{sat} and other soil parameters to calibrate and validate DRAINMOD and Salazar *et al* (2008) showed that a pedotransfer function model such as ROSETTA (Schaap *et al.*, 2001) can be used to accurately estimate K_{sat} values for direct application to DRAINMOD. However, the core model calibration requires measured or observed records of principal variables predicted by the model such as daily values of drainage volumes and water table depths. It is of significant interest to note that the author of the model strongly recommended separate measurements of sub-surface drainage and surface runoff for calibration. However, in cases with open ditch systems, as is specific to this research, the two may be combined and measured as a single daily drainage volume. Calibration can then be performed by summing the predicted sub-surface drainage and surface runoff from DRAINMOD and comparing this to the observed outflows (Skaggs *et al.*, 2012).

The general criterion for calibration and validation requires the size of the area selected to be at the field scale level with drainage characteristics representative of the area being modelled. The calibration period is normally recommended to be at least one year, but, importantly, it should span the range of wet and dry periods and water table conditions normally experienced in the area (Skaggs *et al.*, 2012).

Calibration and validation is aided by time series plots of predicted vs. observed values of water table and drainage volumes. Statistics is normally used to quantify the agreement between measured and predicted values. Table 2 of Skaggs *et al*. (2012) reproduced here as Table 2.3 gave threshold values for classifying these agreements by their respective statistical indicators.

Table 2.3: Threshold values for classifying agreement between predicted and measured water table depth and drainage volume with statistical measures as used for the calibration and validation of DRAINMOD (Skaggs *et al.*, 2012).

		Criteria		
Parameter	**Statistic**	**Acceptable**	**Good**	**Excellent**
Water table depth (daily)	MAE (cm)	<20	<15	<10
	EF	>0.4	>0.6	>0.75
Drainage volume (cm^3 cm^{-2})				
Daily	EF	>0.4	>0.60	>0.75
Monthly	EF	>0.5	>0.70	>0.80
Annual	EF	>0.60	>0.75	>0.85
	NPE	<25%	<15%	<5%

Note: mean absolute error(MAE), Nash-Sutcliffe modelling efficiency (EF) and normalized percent error (NPE).

2.7 Future trends and impacts of climate change on sugarcane production

Over the last few decades an enormous amount of work has been done by researchers in identifying and assessing the impacts of global climate change. These have been excellently organised and assessed in a series of four major reports since 1990 by the Intergovernmental Panel on Climate Change (IPCC) which was set up by the World Meteorological Organisation (WMO) and the United Nations Environment Programme in 1988 (IPCC, 2007a). The Fourth Assessment Report (AR4) was completed in 2007 and it provides valuable information on projected global and regional climate trends along with a comprehensive assessment of the impacts from future climate change on different sectors. The future conditions of global climate was characterized by future Green House Gas (GHG) and aerosol emissions under a collection of four scenarios based on storylines of social, economic and technological development. Often referred to as the SRES (Special Report on Emission Scenarios), these are the A1, A2, B1 and B2 storylines. A detailed description of these scenarios is given in the AR4 by IPCC (2007a).

Climate models are very complex systems comprising of several components, each describing a particular physical phenomenon (atmosphere, ocean and terrestrial processes) attributed to earth and climate science. Notably, the IPCC (2007b) used 23 Atmosphere-Ocean General Circulation Models (AOGCMs) in their evaluation of climate models for predicting future climate trends. These models have been significantly improved since the Third Assessment Report (TAR); however, several limitations in the models remain, affecting uncertainties in magnitude and timing of predicted climate change (IPCC, 2007b).

While future climate trend predictions include assessments of sea level rise; snow, ice and glacial coverage; CO_2 concentrations; ocean acidification; sea level pressure; precipitation and temperature, only the latter two will be discussed in this section as it directly applies to this research.

At the global scale, the mean surface air temperature (SAT) is expected to increase over the 21st century as estimated by all AOGCMs for non-mitigating scenarios and as 1980 to 1999 for the baseline period. The average increase ranges from +0.64°C between 2011 to 2030 for B1, A1B and A2 scenarios, to +4.0°C (range: 2.4°C - 6.4°C) by the late century (2090 - 2099) for the A1F1 scenario. In comparison, precipitation is subjected to greater temporal and spatial variability, and trends when interpreted are vague with low confidence values (IPCC, 2007b). Models with higher resolution (regional scale) are most often used when accurate estimates for trends in precipitation are needed. Nevertheless, for the A1B scenario with the time slice 2080 to 2099, most models show a general increase in precipitation by over 20% at most high latitudes and decreases up to 20% in the Mediterranean, Caribbean and sub-tropical western coasts of each continent (IPCC, 2007b).

At the regional scale of the Amazonia (AMZ), which includes Guyana, the IPCC (2007a) also reported a general increase in temperature over the century using 7 GCMs and the 4 main SRES scenarios. The average increase in temperature varied from +0.7°C in the dry season by 2020 to +6.0°C in the wet season by 2080. Precipitation in the AMZ region was estimated to decrease by -3% in the wet season by 2020 to -40% in the dry season by 2080. Another study at the regional scale, encompassing the boundaries of Guyana only was done by the NCC (2002) to assess the impacts of climate change on the county's environmental, social and economic sectors. The AOGCM from the Canadian Climate Centre (CGCM1) was used to predict precipitation (rainfall), temperature, evaporation and water deficit for two scenarios: 1) carbon doubling and 2) carbon tripling, with 1975 to 1995 being considered as the baseline period. For the 2X CO_2 scenario: temperature was projected to increase by 1.2°C by 2020 to 2040 while precipitation was estimated to decrease by an average 10 mm per month. For the 3X CO_2 scenario, temperature increased by 4.2°C by the latter part of the century (2080 to 2100) while precipitation decreased by 21 mm per month on average for the same time slice.

In totality, the general picture for future climate trends shows an increase in temperature at the global and regional level while precipitation is expected to decrease at the AMZ regional scale. The impacts of these climate change trends have been assessed for ecosystems, coastal systems, the agricultural sector, and urban and industrialized areas. Many of the impacts associated with the agricultural sector may be attributed to water related issues, both directly and indirectly. Water scarcity as a result of a warmer and dryer climate may lead to reduction in yields and other plant growth problems.

Several studies have been done to assess the impacts of climate change on sugarcane growth and production. Knox *et al* (2010) assessed the spatial and temporal impacts of climate change on irrigation water requirements and sugarcane yield in Swaziland by applying a general circulation model (HadCM3) to a sugarcane crop growth model (CANEGRO) and GIS. The study showed that the existing irrigation scheme is inadequate to meet future irrigation demands for nearly 50% of the years modelled (2050s) under the assumption of unlimited water supply and the scenarios A2 and B2.

Marin *et al* (2013) conducted a similar study in southern Brazil where the effects of climate change on sugarcane yield, irrigation demand and water use efficiency (WUE) was evaluated. However, two general circulation models were used in this study (PRECIS and CSIRO) along with CANEGRO. The results showed an increase in simulated stalk fresh mass (SFM) and WUE for the scenarios considered (A2 and B2). Projected yields for the year 2050 were estimated to increase by 15 to 59% as compared to the average yield at the time of the research.

Interestingly, in South Africa, Deressa *et al* (2005) analysed the impacts of climate change on sugarcane production under irrigation and dryland conditions. They found that production was more sensitive to temperature increases as compared to precipitation increases and thus ruled out irrigation as a mitigating option against climate change. Instead, they recommended the development of technologies and management strategies to enhance sugarcane tolerance to warmer temperatures. To this point, Inman-Bamber *et al* (2011) discussed adjusting the sugarcane crop genetics as a measure of adapting to climate change. They also stressed on the importance of studying the physiology of sugarcane at elevated temperatures and CO_2 concentrations as well as drought tolerant varieties.

Lastly, the impacts of climate change on sugarcane yields were investigated in Guyana as given by the NCC (2002). The authors applied the CO_2 doubling and tripling scenarios to the DSSAT model. The results showed an estimated decrease in average yields of 30% for the 2X CO_2 scenario between 2020 to 2040 and a 38% decrease for the 3X CO_2 scenario between 2080 to 2100.

Chapter summary

To summarise and conclude this chapter, the available literature shows that there is a lack of knowledge about the drainage requirements for agricultural fields in Guyana. This presents a challenge to water management as the country's climate, soil type, topography and water resources forms a unique case. Drainage systems are design based on the use of drainage coefficients which are derived through analytical methods of frequency analysis on precipitation records. No previous attempts have been made to validate these drainage coefficients through experimental work. Hence, this field study was done to address this deficiency in the literature for the drainage requirements of sugarcane fields in Guyana.

CHAPTER 3.0 METHODOLOGY

3.1 Experimental site description

The field experiment to measure the components of the water balance was carried out on field CM 57 at La Bonne Intention (LBI), Region #4, Guyana. The coordinates at the centre of the field was recorded as 6° 46' 20.13" N and 58° 04' 38.82" W in UTM zone 21N (WGS84) using a Garmin handheld GPS device. LBI is located approximately 8 km east of the capital city, Georgetown, and it is one of the eight sugar estates of GuySuCo (see Figure 2.2). Figure 3.1 shows the location of the experimental field relative to Georgetown and the factory at LBI estate.

The field was rectangular in shape on a plan view with average dimensions of 110 m in width and 386 m in length (approximately 4.2 ha). It was empoldered with dams and canals on all four sides making it a separate hydrologic unit from the rest of the fields on the estate. A detailed topographic survey of the field and its environ was done using a Leica Total Station. This was done to accurately measure distances and elevations on the field at various points; to ascertain the field dimensions, drain depths and spacing, and the gradient of the land. The results from this survey are shown in Figures 3.2a, b and c.

Figure 3.2a shows the site plan and the layout of the peripheral canals and dams. The canals on the northern and southern sides were cross canals, and on the eastern side it was the navigation/irrigation canal (Middlewalk). These three canals were all connected and a constant water level of 15.94 m GD was maintained throughout the year by GuySuCo. The fourth canal on the western side was the main drainage canal (Sideline) and this collected the discharge from the field via the internal field drain (open ditch).

Generally, the drainage systems on the sugarcane fields in Guyana are surface drainage systems designed to evacuate surface runoff. There were no tile drains for sub-surface drainage. However, sub-surface drainage can occur as lateral groundwater seepage flow to the internal field drain. This field drain ran longitudinally in the middle of the field as shown in Figure 3.2a.

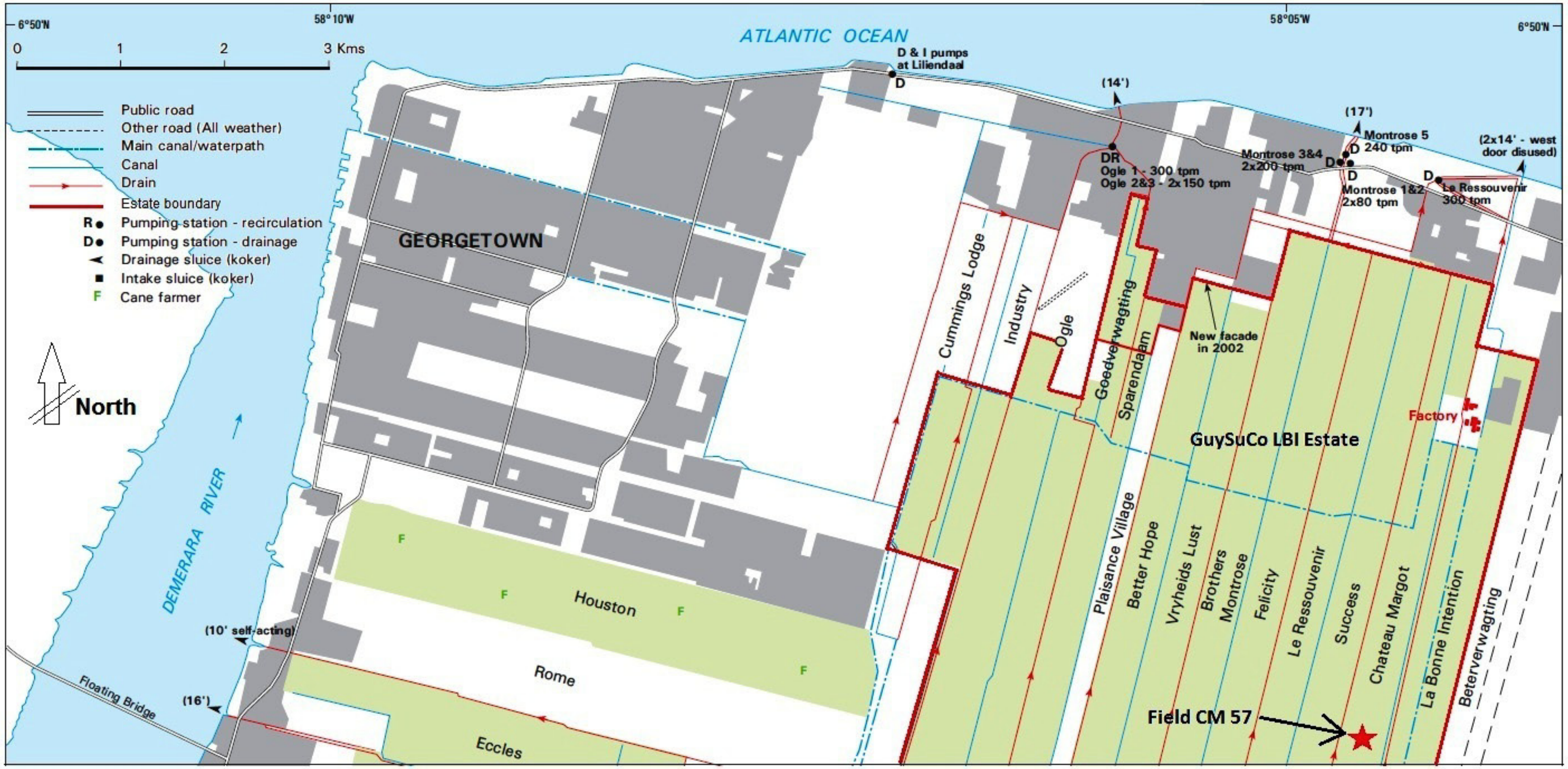


Figure 3.1: Location map of field CM 57 on LBI estate, modified from (GuySuCo, 2003).

Note: to be read in conjunction with Figure 1.1.

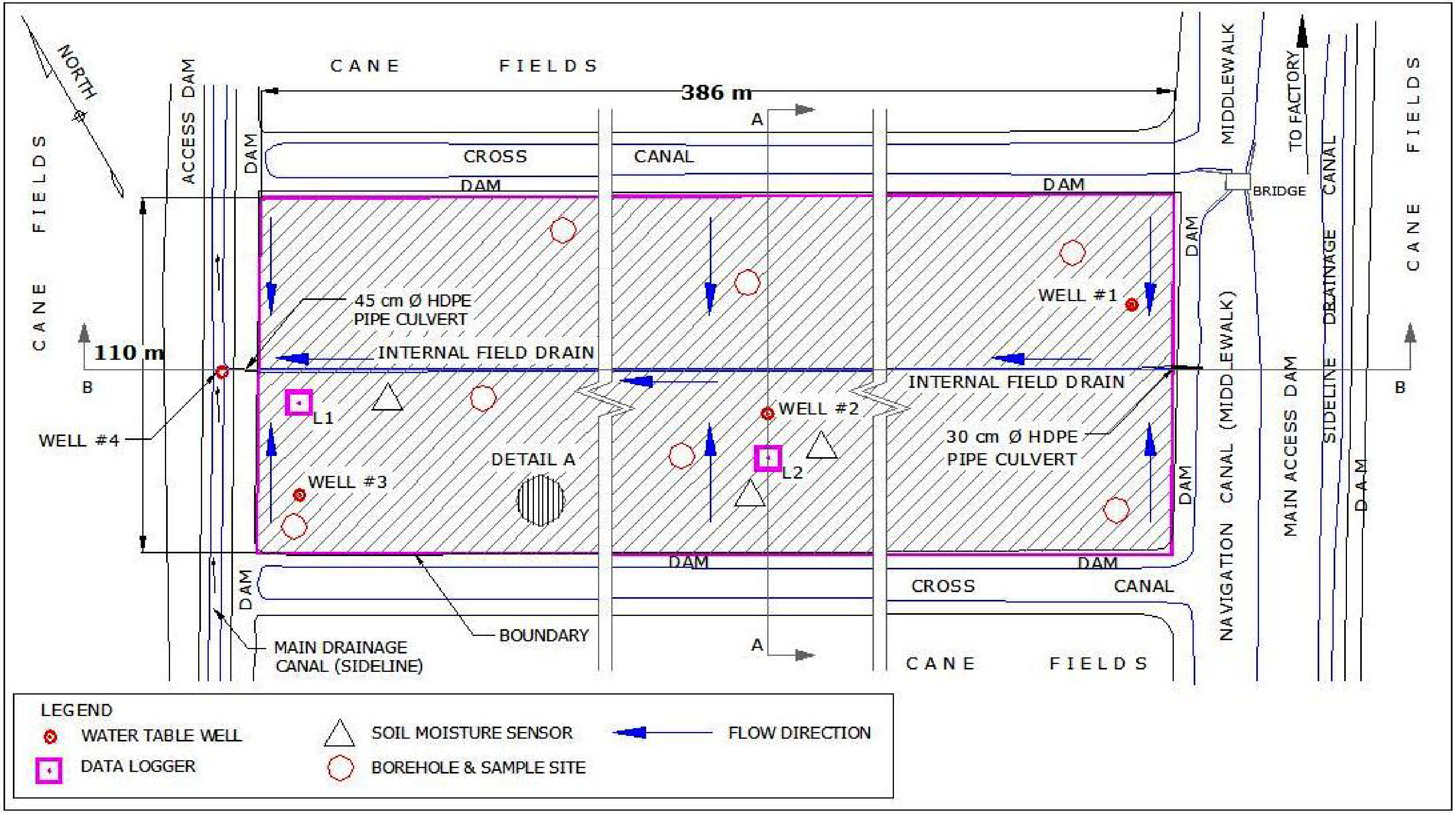
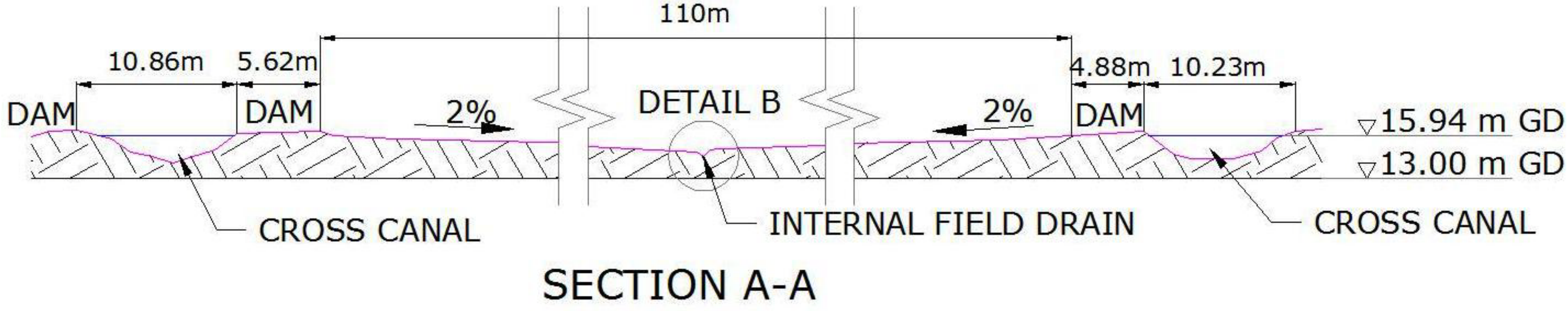


Figure 3.2a: Site plan of field CM 57 showing the layout of the surface drainage system and location of field instruments.



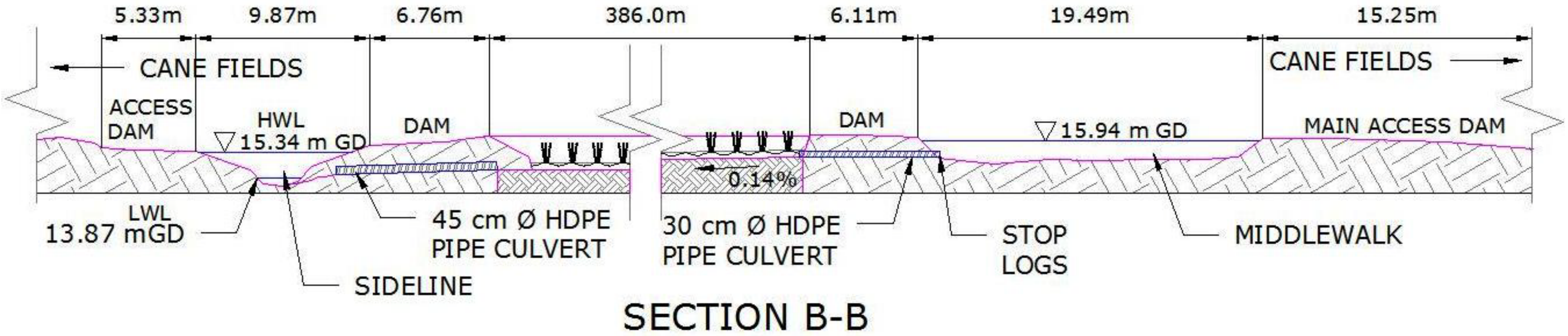


Figure 3.2b: Transverse and longitudinal cross sections of field CM 57 showing surface drainage system and appurtenances.
Note: HWL and LWL are the highest and lowest water levels respectively, as were recorded during the experiment.

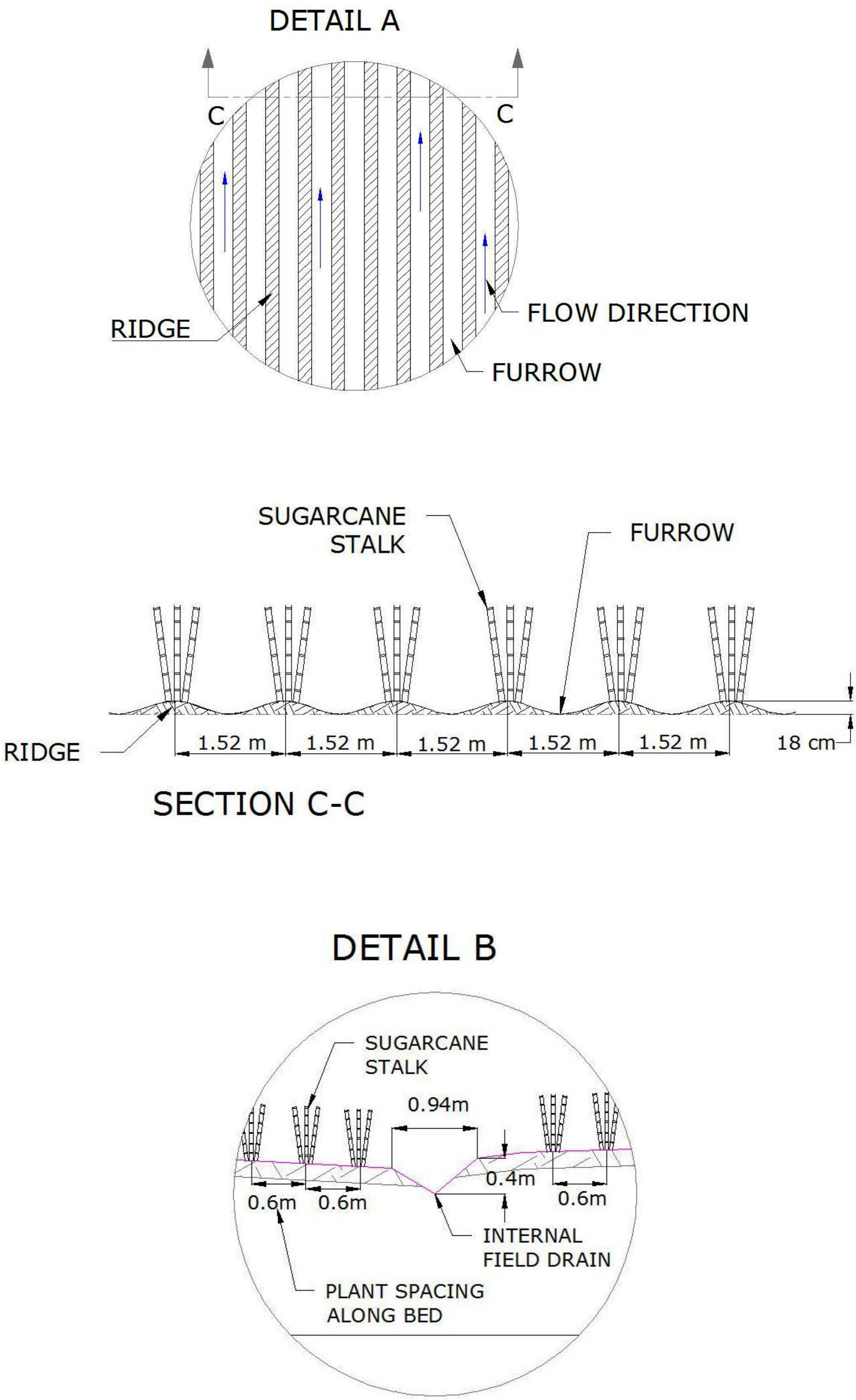


Figure 3.2c: Details showing the ridge and furrow system and the dimensions of the internal field drain.

The average depth of the field drain was 40 cm and this limited the sub-surface drainage to the upper 40 cm of the top soil whenever the groundwater table was in this zone.

Figure 3.2b shows a detailed sectional view along the field drain (Section B-B). The drain ran from east to west with a gentle slope (0.14%). At the eastern end, a 30 cm diameter High Density Polyethylene (HDPE) pipe culvert connected the field drain to the irrigation canal. This allowed for flood fallowing of the field as practiced before land preparation with the stop logs at the inlet acting as a control valve. At the western end, a 45 cm diameter HDPE pipe culvert connected the field drain to the Sideline drainage canal.

The land was shaped to produce transverse slopes towards the field drain as shown in Section A-A (Figure 3.2b). A system of ridges and furrows were formed along these slopes and the sugarcane stalks were planted on the ridges as shown in Section C-C (Figure 3.2c). The ridges were spaced at 1.52 m apart and were approximately 18 cm in height. The cane stalks were placed at 60 cm intervals along the length of each ridge as shown in Detail B (Figure 3.2c). All surface runoff from the furrows were collected by the internal field drain. It is important to note that any sub-surface drainage and surface runoff from the field would then be combined in the internal field drain as a result of this drainage layout. This combined sub-surface drainage and surface runoff was then routed to the Sideline drainage canal as discharge through the 45 cm HDPE pipe culvert. This type of field layout existed for all the research fields at the sugar estate where rigorous breeding programs along with other agronomic studies on sugarcane varieties were carried out by GuySuCo Agricultural Research Unit (GARU). A total of 17 GARU fields existed at the LBI estate and this particular field was selected for its ease of access.

The main commercial sugarcane varieties planted on CM 57 among others, were DB7869 and DB75159 and they were first planted on 6th October, 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) started on 1st November, 2012 and lasted throughout the experimental phase of this research. The third crop was ready to harvest by November, 2013 and all field instruments had to be removed during that month.

3.2 Soil testing

The major soil types along the coastal plains generally consist of heavy clays. A soils map of the area indicated the soil classification at the field as the Whittaker Series, 37 from the FAO soil survey (Steele, 1966). A soils investigation was undertaken to determine the physical properties and characteristics of the soil at the field site. This allowed for the design of the field experiment and specifically the placement of the soil moisture sensors. Three test pits were dug to identify the underlying soil strata. Four distinctive layers up to a depth of approximately 1.5 m were observed in the test pits and representative samples (disturbed and undisturbed) were taken from each layer for laboratory testing. Testing was done at the University of Guyana (Turkeyen Campus) and at McGill University (Macdonald Campus). Table 3.1 summarises the different laboratory tests that were done along with their respective test method. Samples from each layer were transported to McGill University for the particle size analysis and the soil water characteristic curve (SWCC) test because the laboratory at the University of Guyana was not equipped with the appropriate instruments for these tests.

Table 3.1: List of laboratory tests for soil properties of samples collected from field CM 57.

Soil Test	Standard	Sample State	Laboratory
Atterberg Limits	ASTM D 4318 - 00	Disturbed	University of Guyana
Particle Size Analysis	ASTM D 422 - 07	Disturbed	McGill University
Specific Gravity	ASTM D 854 - 02	Disturbed	University of Guyana
Water Content	ASTM D 2216 - 98	Disturbed	University of Guyana
Soil Water Characteristics Curve	ASTM D 6836 - 02	Undisturbed	McGill University
Bulk Density	ASTM D 2937 - 00	Undisturbed	University of Guyana

Throughout the remainder of the data collection period, the soil layers were observed and recorded at several other locations. Auger holes were dug for the water table wells, moisture content samples and for in-situ hydraulic conductivity tests. Also, other test pits were dug for bulk density and SWCC test samples. Figure 3.2a shows the location of the test pits/boreholes and sampling sites in the field.

In-situ testing for Saturated Hydraulic Conductivity

The saturated hydraulic conductivity (permeability, K_{sat}) of the soil is an important parameter for analysing groundwater flow to drainage systems. In this study, this parameter was needed as an input for DRAINMOD. The in-situ permeability tests by the Hooghoudt auger-hole method (Beers, 1983) was done to obtain K_{sat} values. The complete standardized auger-hole method test kit from Eijkelkamp was used to determine the K_{sat} values for layers 2 and 3 of the 4 layer soil profile. The logistics of transporting the bulky and heavy test kit to the field site did not allow for the other 2 layers to be tested as 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 following the methodology developed by Jabro (1992) and as applied to DRAINMOD by Yang (2008).

3.3 Measured components of the field water balance

The experimental field was instrumented to allow for the continuous measurement of several hydrological and meteorological variables. This was necessary for computing the components of the field soil-water balance and for calibrating and verifying DRAINMOD. These components were considered in the following equation.

$$P - ET_c - (D + RO) \pm \Delta S = 0 \qquad (3.1)$$

where P is the precipitation (cm), ET_c is the crop evapotranspiration (cm), D+RO is the combined sub-surface drainage and surface runoff (cm) and ΔS is the change in soil moisture storage (cm). Equation 3.1 is a variant of equation 2.2 (Chapter 2) which was simplified since no irrigation was applied during the data collection period. Also capillary rise was assumed to be included in the crop evapotranspiration. The sub-surface drainage (D) and surface runoff (RO) components were combined, as a total field discharge. This was done because the measured discharges from the field contained both sub-surface drainage and surface runoff, which was a result of the layout of the field drainage system as previously discussed.

The hydrological variables measured included soil moisture, groundwater table levels, and the field discharge (D+RO). The meteorological variables included rainfall, air temperature, relative humidity, solar radiation and wind speed. The latter four of the meteorological variables were used as input for the computation of reference evapotranspiration based on the FAO-56 PM ET model (Equation 2.3). This was done using the FAO's ET_o Calculator (Raes, 2012) with the local weather station parameters. The program computed the ET_o which was then converted to ET_c by applying the single crop coefficient (K_c) for sugarcane at the various growth stages as detailed in section 2.4.3. However, for the late stages, the coefficient of 1.25 was used instead of FAO's 0.7 to work out the water balance as recommended by Inman-Bamber and McGlinchey (2003).

Initially, the experiment was designed to measure soil moisture at various depths on a continuous basis using smart sensors. However, the connectors for these sensors were compromised during the wet season and they stopped working altogether by June 26, 2013. The moisture content for the remaining period of the experiment was therefore measured by taking gravimetric samples. Additionally, backflows from the Sideline drain into the field were observed and recorded during the wet season, sometimes lasting for three or more days. This made it impossible to separate the D+RO component from the backflow.

A daily soil-water balance was computed for a maximum root depth of 80 cm for sugarcane as observed in the field for a mature cane stalk. The daily water balance was calculated by adding the algebraic sum of $P - ET_c$ to compute the daily soil moisture for the 80 cm profile, commencing with an initial moisture content which was measured in the field. This calculated moisture content was kept to a maximum value of 44.26 cm (100% saturation) and any moisture in excess was considered as D+RO. The ΔS component was then calculated from a daily change in calculated soil moisture. This was then compared to the measured ΔS component from daily measured changes in soil moisture.

3.4 Field instrumentation

Two Onset Hobo® U30/GSM data loggers were installed on the site at different locations (Figure 3.2a), each with analog sensor ports and with expander kits allowing for up to ten smart sensors to be connected. Each logger was powered by a 4.5 V battery that was continuously recharged with a 6 W solar panel. The first logger (L1) was used to establish a field weather station that was mounted on a 2 m tripod kit. The sensors that were connected to Logger 1 were: tipping bucket rain gauge, temperature and RH sensors, silicon pyranometer, wind speed, four - 10HS soil moisture smart sensors, and two KPSI 700 submersible level pressure transducers that were connected to the analog ports.

These sensors, with the exception of the soil moisture sensors and the transducers, were used to measure the meteorological variables previously listed. The transducers were used to record the headwater and tailwater levels in the 45 cm diameter HDPE pipe culvert. This enabled all discharges (sub-surface drainage flows and surface runoff, D+RO), which were routed from the field to the outlet, to be computed indirectly as given by the United States Geological Survey (USGS) culvert hydraulics formulae for the six different flow types (Bodhaine, 1968). See Appendix C for the equations and charts used in computing the discharges from observed water level readings.

L1 was placed at the western end of the field closest to the outlet HDPE pipe culvert to minimize the use of electrical wires connecting the transducers to the logger. Also, to reduce the effects of distorted aerodynamic resistance from the canopy, the wind speed sensor was placed at 3.7 m from the ground and the necessary adjustments were made when computing the ET_o. All data on L1 were logged at 10 min intervals from 16 March to 26 November, 2013. As GuySuCo commenced their harvest season by the end of November, all instruments had to be removed prior to harvest.

The second data logger (L2) was also strategically placed at midfield and used solely for soil moisture sensing. This was done to maximise the use of available ports on each logger. A total of eight 10HS soil moisture sensors were connected to L2 in two locations. Each location had a set of four sensors placed in the same configuration as the first set that was connected to L1. For each location, a sensors was placed in a vertical position at the centre of each distinctive soil layer (4 layers from the soil investigations, see section 3.2) with depths of 11.0, 44.5, 82.5 and 120.5 cm from the soil surface at the ridges.

Water table observations were done by installing three observation wells along a diagonal in the field (see Figure 3.2a). Auger holes (4 cm diameter) were bored to a depth of 1.5 m and perforated polyvinyl chloride (PVC) pipes were installed with a 1 m extension above the ground. A Solinst Levelogger® (model 3001) with built- in logging and storing capabilities was placed in each well to record the water depths at 10 min intervals. The leveloggers were suspended from the top of the wells with stop caps and connecting wires. A fourth levelogger with a similar PVC well was used to monitor the water levels in the Sideline drain. This was done to identify periods of backflow of water into the field from the Sideline drain. The compensating Barologger® (Solinst, 2012) was also used to adjust the readings on the leveloggers for atmospheric pressure. This was installed at the upper part of the well in the Sideline drain, and above the potential maximum flood level. Also, a well stick was fabricated and used to verify the water table depths in each well over the experimental period. The well stick was fitted with an acoustic device that emits sound once in contact with water. Water table data were logged from 16 March to 19 November, 2013. See Figure 3.2a for the location of all field sensors.

3.4.1 Sensor calibration

The soil moisture sensors were calibrated against gravimetric samples. The measured and gravimetric moisture contents were then compared and regression analysis was used to generate a calibration curve. Calibration was done for the uppermost layer only, as the wet season began shortly after the first test and then the sensors were compromised with L2 being removed by the time the second dry season started. Nevertheless, the curve was used for layers 1 to 3, as their soil textures were very similar. See Appendix B for the calibration curve.

The pressure transducers were calibrated by taking field measurements of water depths at the inlet and outlet sections of the 45 cm diameter HDPE pipe culvert representing the headwater and tailwater elevations respectively. These were then compared to the computed depths from the transducers. See Appendix B for the results for each transducer.

3.5 Simulation and modelling with DRAINMOD

The main input parameters for DRAINMOD can be placed into four main groups as follows: weather data, soils data, drainage system, and crop data.

3.5.1 Weather data

The weather datasets included daily precipitation (rainfall), temperature and/or potential evapotranspiration. Daily records of rainfall, and minimum and maximum temperature from the experimental weather station at CM 57 were used to create the input weather files for the model during the calibration and validation period. Although ET_o data was available for use as input for the model during calibration, the monthly ET factors were used instead. This was done because the model was being calibrated for use with historical climate data, which excluded ET_o datasets as they were not available. The monthly ET factors were computed as the ratio of PET (Thornthwaite, 1948) to the ET_o (FAO PM-56) for each month in 2013 using the measured meteorological variables from L1. Meteorological data from GuySuCo's weather station, located 3.5 km north east of L1, were used to supplement the 2013 datasets for January, February, December, and the missing days in March and November.

Long term climate data for Georgetown was collected and used for simulations with DRAINMOD. The data was recorded at Georgetown's Botanical Garden meteorological station. 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). An analysis of the rainfall data was done to determine the wettest and average years in terms of total annual rainfall. The annual rainfall data was also fitted to the normal frequency distribution. This was done to determine the return period for the year of interest. Similarly, the maximum one month and three consecutive month totals were fitted to the Gumbel distribution, given that they were extreme in nature, and the return period for the critical event was determined.

3.5.2 Soils data

The soils data for DRAINMOD included the soil water retention parameters (from SWCC) and the saturated hydraulic conductivity (Ks). The SWCC for each of the four soil layers on the field was generated from the laboratory test results on the undisturbed samples collected. The K_s values were measured in the field using the Hooghoudt auger-hole method for layers 2 and 3. It was computed for layers 1 and 4 using the equation developed by Jabro (1992) following Yang (2008) with an adjustment to the constant. This yielded the following relationship:

$$\log K_s = 8.91 - 0.81 \log(silt\%) - 1.09 \log(clay\%) - 4.64(BD) \quad (3.2)$$

where K_s is the saturated hydraulic conductivity (cm h^{-1}), silt% and clay% are from the particle size distribution and BD (g cm^{-3}) is the bulk density. The percentage error between measured K_s and predicted K_s from equation 3.2 was 0.14% for layer 2. This layer was used to derive the adjusted constant as its properties were a better match to those used in Jabro's work as compared to layer 3. Another important and related soil parameter that is often estimated is the lateral saturated hydraulic conductivity. This was approximated as twice the K_s value for each soil layer after parameter sensitivity analysis.

3.5.3 Drainage system

The drainage system parameters for DRAINMOD included the spacing of the drain and its depth from surface. Since there were no tile drains in the field and the existing field drain was a single, open ditch along the centre, a virtual tile drainage system was assumed for calibration. A drain spacing of 40 m was chosen initially and then calibrated in the model. However, the actual average field drain depth of 40 cm was used as an initial parameter. The effective radius of the drain was given as 30.48 cm for ditches (EFH, 2011). The distance to the impermeable layer was arbitrarily estimated as 3 m and the maximum surface storage as 0.5 cm; these values were further adjusted during calibration.

3.5.4 Crop data

The crop data used in DRAINMOD consisted mainly of the crop rooting depth with time. For sugarcane this was chosen based on the work done by several researchers (Battie Laclau & Laclau, 2009; Gayle *et al.*, 1985; Smith *et al.*, 2005) and adjusted to suit GuySuCo's Crop Calendar. Also, the maximum root depth was observed in the field for a mature cane stalk and it was found to be approximately 80 cm. Table 3.2 gives the crop root depth vs. time as used in DRAINMOD. It should be noted that a root depth of 3 cm during the fallow period from December to January was chosen so that DRAINMOD can compute evaporation during this period (Skaggs, 1978).

Table 3.2: Crop rooting depth for sugarcane grown in Guyana

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

3.5.5 Calibration and validation

The water table levels from the three observation wells were averaged and used as the measured/observed variable in the evaluation process. The dataset was split into two with 1st April to 31st August, 2013 being used for the calibration period and 1st September to 19th November, 2013 being used for the validation period.

3.5.6 Simulations for assessing the drainage coefficient

As previously mentioned, the climate data from the Georgetown meteorological station were used for simulating the hydrology of the field. The daily rainfall, minimum and maximum temperatures from the wettest and average periods were used to simulate the water balance using the calibrated model. Additionally, the respective year before the year of interest was used in the simulation as the warm up period. The output data from the simulations were then used to compute the drainage rates for the respective average and wettest periods. The drainage rate was taken as the combined sub-surface drainage and surface runoff (D+RO) components from the DRAINMOD output file. The sub-surface drainage values were adjusted by the correction factor 4/7 as this was the ratio of the actual drain depth (40 cm) to the calibrated/virtual drain depth (70 cm). These simulated drainage rates were then compared to historical design drainage coefficients used in Guyana. Also, a simulation of the water balance for the year 2013 was done and the results were compared to those of the measured water balance for the matching period (15th March to 26th November). The drainage rates for this year was also computed so that the hydrology under current conditions can be assessed.

3.6 Evaluation of model performance

The model performance for calibration and validation was evaluated using the statistical indicators from Table 2.3 (section 2.6.2) for daily water table levels. In addition, two other statistical indicators were used, namely the IoA and the Percentage Bias (PBIAS). Altogether, they were computed using the following equations:

$$MAE = \frac{1}{n}\sum_{i=1}^{n}|P_i - O_i| \tag{3.3}$$

$$EF = 1.0 - \frac{\sum_{i=1}^{n}(O_i - P_i)^2}{\sum_{i=1}^{n}(O_i - \bar{O})^2} \tag{3.4}$$

$$IoA = 1.0 - \frac{\sum_{i=1}^{n}(O_i - P_i)^2}{\sum_{i=1}^{n}(|P_i - \bar{O}| + |O_i - \bar{O}|)^2} \tag{3.5}$$

$$PBIAS = \frac{\sum_{i=1}^{n}(O_i - P_i)}{\sum_{i=1}^{n} O_i} \tag{3.6}$$

where *n* is the total number of data points, P_i is the simulated or predicted value and O_i is the observed or measured value for the: MAE after Willmott (2012), Nash-Sutcliffe Model Efficiency (EF) after Nash & Sutcliffe (1970), IoA after Wilmott (1981), and Percentage Bias (PBIAS) after Morasi *et al.* (2009). The former statistic was used as an absolute measure given in the unit of the values, and the latter three as relative measures. Legates and McCabe (1999) recommended the use of at least one absolute and one relative measure for evaluating model performances. In assessing the PBIAS, Morasi *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).

CHAPTER 4.0 RESULTS AND DISCUSSION

4.1 Field results

4.1.1 Soil physical properties

The soil type at field CM 57 was given as the Whittaker Series, 37 (Steele, 1966), having poor drainage and permeability properties. The visual features observed from the open test pits and auger holes that were dug during the soil investigation phase, were consistent with the descriptions given in the FAO soil survey report for this series. Measured and computed soil properties (physical) from in-situ and laboratory tests are summarised in Table 4.1. The given values are the field averages for the respective soil layer. The soil investigations showed a total of four distinct layers of soil up to a depth of 1.4 m. The upper three layers were classified as "Clay" according to the USDA soil textural classification system. These three layers were of particular importance in soil moisture calculations given that the maximum root depth observed was 0.8 m. The clay fraction of the first three layers exceeded 60% while the remaining parts comprised of predominantly silt and traces of sand. The fourth layer was classified as "Silty Clay" with an even mix of the clay and silt fractions.

Table 4.1: Summary of the measured soil properties for the Whittaker Series, 37 (# of samples, n = 12).

Layer	Depth (cm)	Particle Size Distribution (%)			USDA Texture	Atterberg Limits (%)			Bulk Density (g cm^{-3})	Particle Specific Gravity	Saturated Hydraulic Conductivity (cm hr^{-1})
		Clay	Silt	Sand		W_L	W_P	I_P			
1	0-22	63	35	2	Clay	88	41	47	1.23	2.69	0.99[a]
2	22-65	65	32	3	Clay	90	43	47	1.29	2.71	0.54
3	65-100	66	32	2	Clay	71	38	33	0.94	2.70	0.33
4	100-141	45	45	10	Silty Clay	67	44	23	1.11	2.74	4.10[a]

[a] Calculated based on particle size and bulk density following Jabro (1992).

The Atterberg limits W_L, W_P and I_P in Table 4.1 are the volumetric water contents at the liquid limit, plastic limit and plasticity index respectively. The I_P of the upper three layers indicated their highly plastic nature which is characteristic for heavy clay soils of the montmorillonite type. These clays tend to swell significantly upon wetting and have a very low permeability. It is for this reason that tile drains are not as effective as open ditches for drainage under these conditions.

The SWCC are given in Figure 4.1 and are based on field averages for each soil layer. The curves were consistent with generic soil water curves for clay type soil. The volumetric moisture content ranged from 56% to 27% over the applied pressure of 0 to 15,296 cm (0 to 15 bars) for all four soil layers. Figure 4.1 shows a trend where the moisture retention curve for each layer is higher on the graph as depth increases. This is due to variations in the layer porosity as a result of differences in soil texture. Also, the slope of the curves were fairly similar and as a result the available water content (AWC) for the upper three layers was constant at an average of 7.1%. The AWC was computed from the SWCC as the difference in volumetric moisture content between field capacity at 336.5 cm (0.33 bars) and wilting point at 15,296 cm (15 bars) as given by Smedema and Rycroft (1983). The SWCC for each layer is given in Appendix D.

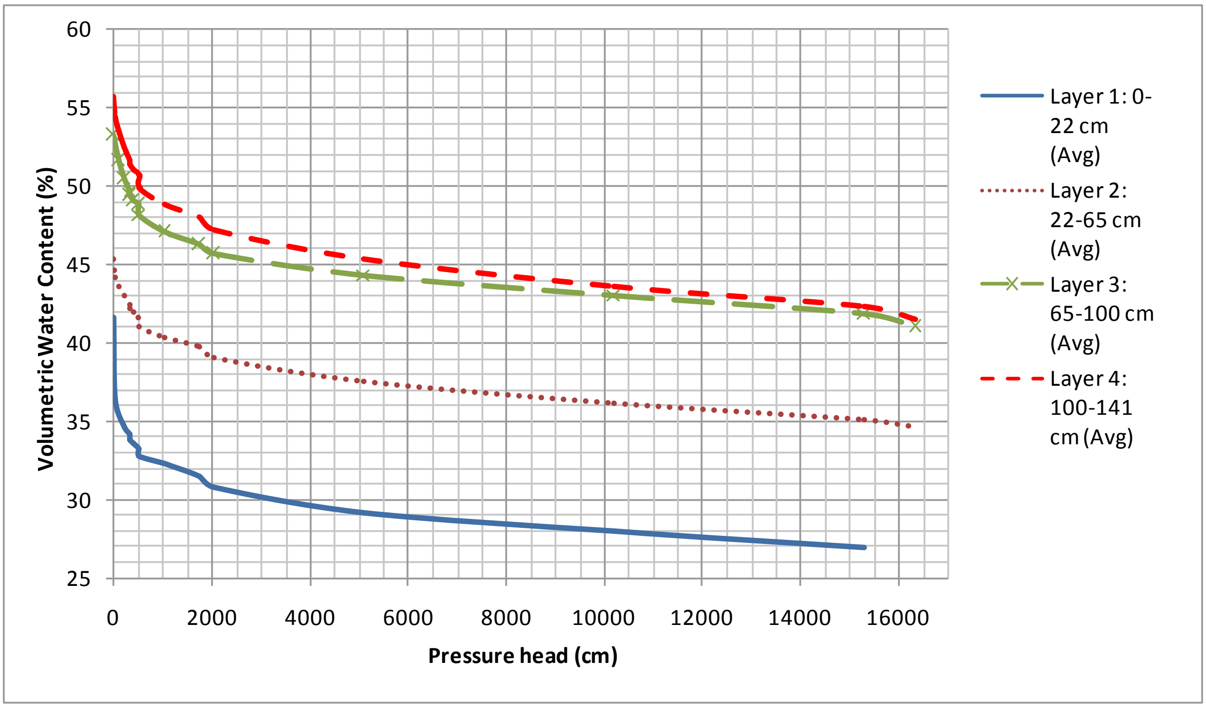


Figure 4.1: Soil Water Characteristic Curves for each soil layer of the Whittaker Series, 37 (# of samples, n = 6)

4.1.2 Meteorological data

The measured meteorological variables at the field's weather station for the period March 16 to November 26, 2013 are given in Table 4.2 and are the average daily values for the month, with the exception of rainfall, which is given as the monthly total.

Table 4.2: Summary of the measured meteorological variables from the Hobo Weather Station at Field CM 57.

Month	Rainfall (mm)	Temperature (°C)		Relative Humidity (%)		Wind Speed ($m\ s^{-1}$)	Solar Radiation ($W\ m^{-2}$)
		Min	Max	Min	Max		
March[a]	55.26	24.52	30.51	66.69	93.72	1.97	224.91
April	110.01	24.63	30.77	68.98	93.83	1.59	209.49
May	285.20	24.18	30.79	73.26	97.69	1.08	190.34
June	343.60	24.23	31.26	71.76	97.97	0.93	217.92
July	343.60	23.34	31.96	67.28	98.94	0.59	225.42
August	249.80	23.54	32.53	65.27	99.16	0.50	229.60
September	101.80	24.02	33.25	62.56	94.09	0.83	237.89
October	87.40	24.45	32.95	62.93	92.64	1.09	220.49
November[a]	131.40	23.82	32.07	65.89	94.30	1.03	188.40

[a] Data set does not cover the entire month.

The months of June and July were equally the maximum during the data collection period with a total of 343.6 mm. Daily temperatures ranged from 23.3 °C to 33.25°C while relative humidity ranged from 62.56% to 99.16% for the period. Figures 4.2 and 4.3 shows the monthly distribution of rainfall and air temperature respectively from the observed dataset. For comparison, long term climatic trends from adjacent weather stations at GuySuCo's LBI and Georgetown's Botanical Garden meteorological stations were also included. Figure 4.2 indicated that the natural wet season from May to July was noticeably above normal for the year 2013 extending well into August. While January was unusually dry, the short season from February to April was also drier than average. However, the overall seasonal trend of two wet and dry periods was visible. Additionally, the long term trends for the station at Georgetown and LBI were very similar, and hence the data used from the former station was valid for the DRAINMOD simulations at LBI. The monthly average temperatures were very consistent except for the minor fluctuations at the GuySuCo station for 2013. This station did not have a continuous record of long term daily minimum and maximum temperatures.

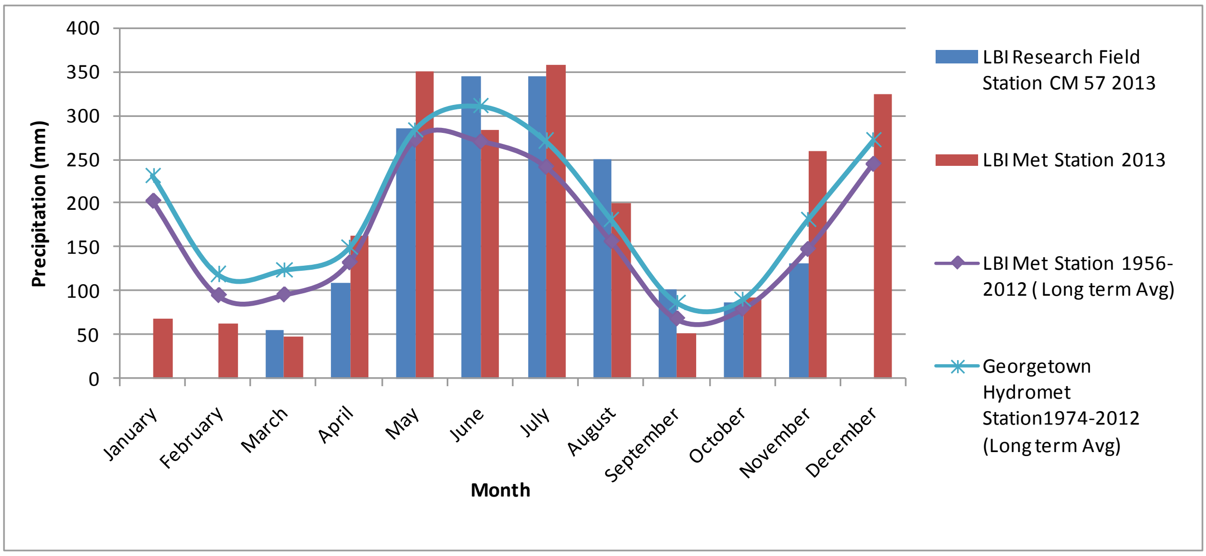


Figure 4.2: Monthly Precipitation distribution for Field CM 57 and adjacent stations.

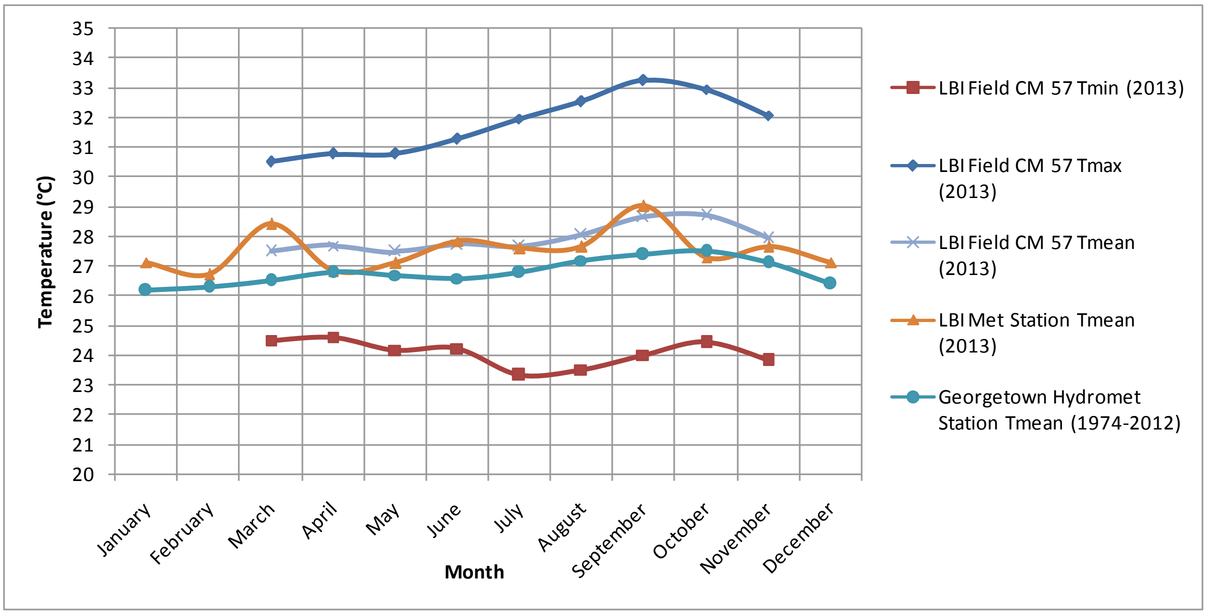


Figure 4.3: Monthly Air Temperature distribution for Field CM 57 and adjacent stations.

4.1.3 Field soil-water balance

The measured field meteorological and hydrological data were used to compute the daily soil-water balance over the period covering March 16 to November 26, 2013. Table 4.3 summarises the components of the field water balance for each month. The measured components were i) precipitation (170.8 cm), ii) crop evapotranspiration (129.1 cm), iii) combined sub-surface drainage + surface runoff (48.8 cm), and iv) the net change in soil moisture (2.06 cm).

The total ET_c accounted for 75.6% of the total precipitation for the study period. This was in good agreement with other water balance studies for both rainfed and irrigated areas of sugarcane fields globally, as several studies gave ET components varying from 64% to 87% of the local precipitation and/or irrigation (Ghiberto *et al.*, 2011; A. L. C. Silva *et al.*, 2011; V. P. R. Silva *et al.*, 2012; Wiedenfeld, 2004). The maximum monthly ET_c was computed for September which coincided with the long dry season.

Sub-surface drainage and surface runoff were summed together as measured in the field (D+RO). The values shown are the net monthly flows through the culvert and the negative values indicate a net backflow from the Sideline drain into the internal field drain. This was experienced during periods of intense rainfall as the discharge from other fields upstream of CM 57 increased the stage level in the Sideline drain, and submerged the outlet section of the culvert. Furthermore, majority of the flows through the culvert occurred under submerged conditions, fluctuating between outflow (field discharge) and backflow several times in a given day. However, when all monthly totals were summed together, a net field discharge of 48.83 cm was computed, accounting for about 28% of the precipitation. This value was marginally higher than published values of 15% and 20% from V.P.R. Silva *et al.* (2012) and Ghiberto *et al.* (2011) respectively. This may be as result of differences in the soil physical properties, as more surface runoff can be expected from the heavy clays of Guyana.

Negative values in the soil moisture columns of Table 4.3 indicate net losses in soil moisture while positive values indicate net gains in soil moisture for the field. By comparison, a water balance equation was used to calculate the net change in soil moisture from the precipitation and crop ET measurements (section 3.3), giving a value of 5.25 cm. The difference in values may be attributed to the lack of continuous measured soil moisture data, as we were only able to undertake gravimetric soil moisture measurements every 27 days on average. This was evident from comparing the monthly values in the table, as there is a greater deviation in the month of July (-13.4 to -1.07 cm) when gravimetric measurements commenced.

Table 4.3: Summary of the measured soil-water balance at Field CM 57.

Month	P[b] (cm)	ET_c[c] (cm)	D + RO[d] (cm)	ΔS_{mea}[e] (cm)	ΔS_{cal}[f] (cm)
March[a]	5.53	8.74	0.00	0.22	-3.21
April	11.00	15.18	0.00	5.04	-4.17
May	28.52	13.79	-48.66	15.32	14.73
June	34.36	14.88	4.03	-1.97	0.67
July	34.36	15.66	46.38	-13.40	-1.07
August	24.98	16.10	34.78	-0.21	0.79
September	10.18	16.65	-9.30	4.16	-5.91
October	8.74	16.44	4.95	1.76	6.00
November[a]	13.14	11.64	16.65	-8.86	-2.59
TOTAL	**170.81**	**129.06**	**48.83**	**2.06**	**5.25**

[a] Data set does not cover the entire month, [b] Precipitation, [c] Crop Evapotranspiration, [d] Sub-surface Drainage + Surface Runoff, [e] Measured Change in Soil Moisture, [f] Calculated Change in Soil Moisture.

4.1.4 Observed water table levels

Daily water table levels for the three observation wells in the field are shown in Figure 4.4 for the period March 16 to November 19, 2013. The water table levels were reduced to the common Georgetown datum (GD) since there were some small variations in land level at each well ranging from +9.3 cm to -14.0 cm, when compared to an average land elevation of 15.484 m GD. The average water table level of the three wells was computed and is also shown in Figure 4.4.

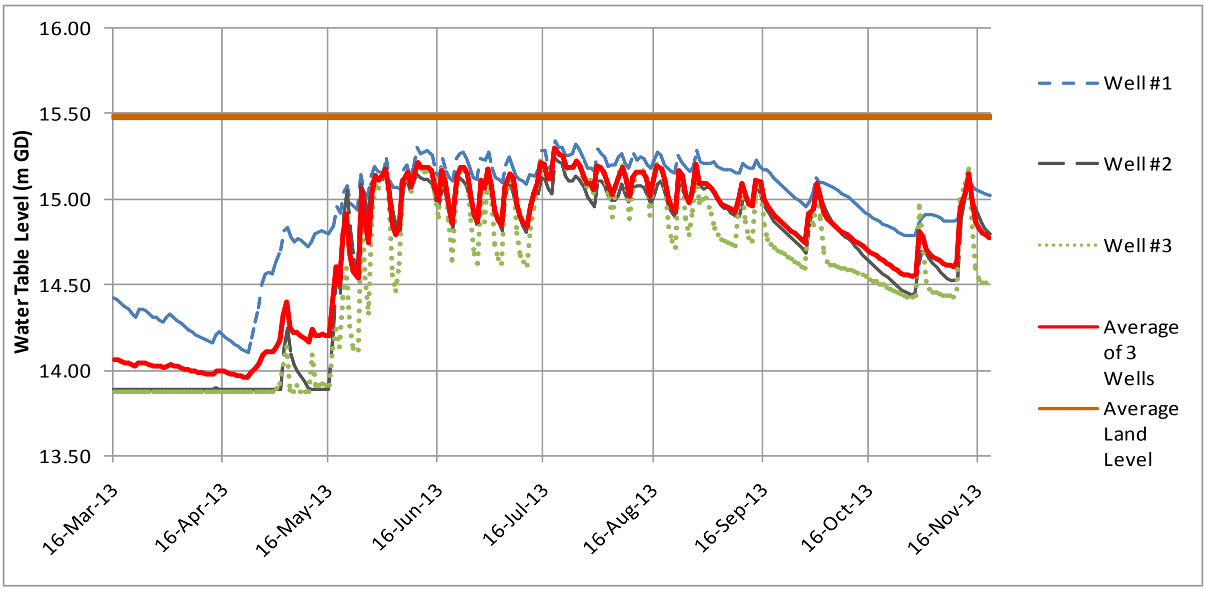


Figure 4.4 Daily water table levels for the 3 observation wells in the field.
Note: Reduced elevations are given in m GD and average land elevation is 15.484 m GD.

Figure 4.4 showed that the water table levels began to rise in late April coinciding with the start of the long wet season. More importantly, the average water table level fluctuated within the upper 80 cm of the soil profile for the majority of the wet season from late May to late August. Additionally, the water table levels rarely fell below 1.0 m of the average ground level during the long dry season from September to November. This gave an indication of how poor the drainage properties of the heavy clay soils are given that ET_c was at its maximum during this dry period.

A detailed examination of the water table levels for the wells reveals that Well #3 had greater fluctuations during the wet season. This may be as a result of the well being closer to the Sideline drain as compared to the other two wells. Secondly, minor variations in soil texture at this location may contribute to deviations in the hydraulic conductivity of the soil layers.

Well #4 was used to monitor the surface water levels in the Sideline drain. This was used along with the pressure transducer's tailwater levels, to determine the periods for backflow calculations and for submerged discharges through the culvert. The results for this well are presented in Appendix C.

4.2 Calibration and Validation of DRAINMOD

The calibration of DRAINMOD involved adjusting key input parameters to obtain acceptable agreement between model outputs and measured or observed values. Conventionally, DRAINMOD is calibrated by comparing simulated water table levels, sub-surface drainage outflows and surface runoff against their measured counterparts. However, because of the layout of the field drainage system (as discussed in section 3.1), the latter two outputs were combined to allow for comparison with the measured field discharge (D+RO) in accordance with Skaggs *et al.* (2012). Unfortunately, the prolonged periods of backwater flow from the Sideline drains into the field did not allow for measured daily outflow values to be isolated. Instead, it yielded a net field discharge when the monthly totals were balanced. Hence, only the observed water table levels in the field were used for evaluating the model during both the calibration and validation process.

The average water table levels from the three observation wells were used as the measured/observed variable in the evaluation process. The dataset was split into two with the long wet season being used for the calibration period and the long dry season being used for the validation period. These spanned the climatic norms of Guyana's coastal region, and therefore, they covered the full range of water table levels experienced in the region fitting the criterion set out by Skaggs *et al.* (2012). It must be noted that no continuous record of water table levels or flow discharges for sugarcane fields in Guyana existed prior to the experiments done in this research.

The calibration process was done following the methodology applied by He *et al.* (2002) for adapting DRAINMOD to simulate water table levels in coastal plain soils assuming a virtual tile drain system. Therefore, the parameters calibrated were the drain spacing, depth of drain from the surface, distance to impermeable layer, maximum surface storage, Kirkham's depth for flow to drains, drainable porosity, saturated hydraulic conductivity and the monthly ET factors. After calibration, the parameters were kept constant (except for the initial depth to water table) and the model was simulated for the validation period.

4.2.1 Initial and Calibrated Input Parameters

The initial and calibrated input parameters for DRAINMOD are given in Table 4.4 under the categories of drainage system, soil and weather. For the drainage system, the actual field values for drain depth and initial depth to the water table were used as initial values. Also, the drainage coefficient chosen was the upper limit of the historical design DC (3.5 - 5.0 cm day^{-1}) as used for the existing drainage system. The drainable porosity and saturated hydraulic conductivity for soil layer 4 were the only soil parameters adjusted for calibration. The monthly ET factors were also adjusted during calibration.

4.2.2 Model Evaluation

The simulated water table levels for the model calibration and validation was evaluated using the statistical parameters given in section 3.6. A plot of the daily simulated vs.

observed water table levels against daily precipitation is given in Figure 4.5 for the calibration phase. A similar plot for the validation phase is given in Figure 4.6. For the calibration phase, the predicted water table levels varied from 192 cm to 10 cm below the ground level as compared to observed values of 148 cm to 14 cm. The disparity at the deeper water table levels may have been as a result of the depth of the bored wells being limited to 1.5 m. This resulted in a high MAE of 18.91 cm between the predicted and observed water table levels. Nevertheless, the MAE was assessed as acceptable and the value was well within the ranges of values reported from previous studies in the literature (Gayle *et al.*, 1985; He *et al.,* 2002; M. Singh *et al.,* 1994; Skaggs,1982).

Table 4.4: Initial and calibrated parameters for DRAINMOD.

Parameter	**Initial Value**	**Calibrated Value**	**Unit**
Drainage System			
Depth of drain from soil surface, B	40	70	cm
Spacing between drains, L	4000	1500	cm
Effective radius of drains, R_e	30.48	30.48	cm
Distance to impermeable layer, H	300	160	cm
Drainage coefficient, DC	5	5	cm day^{-1}
Initial depth to water table, W	140.63	140.63	cm
Maximum surface storage, Sm	0.5	0.25	cm
Kirkham's depth for flow to drains, SI	0.5	0.25	cm
Soil			
Drainable porosity, M	0.166 - 0.0026	0.599 - 0.038	cm cm^{-1}
Saturated Hydraulic Conductivity, K_s (Layer 4)	4.1	1.6	cm hr^{-1}
Weather: Monthly ET Factors			
January	0.86	1.15	-
February	0.80	1.01	-
March	0.97	1.05	-
April	0.78	1.06	-
May	0.73	1.07	-
June	0.76	1.13	-
July	0.81	0.96	-
August	0.78	1.02	-
September	0.74	0.90	-
October	0.73	0.80	-
November	0.73	0.79	-
December	0.68	0.75	-

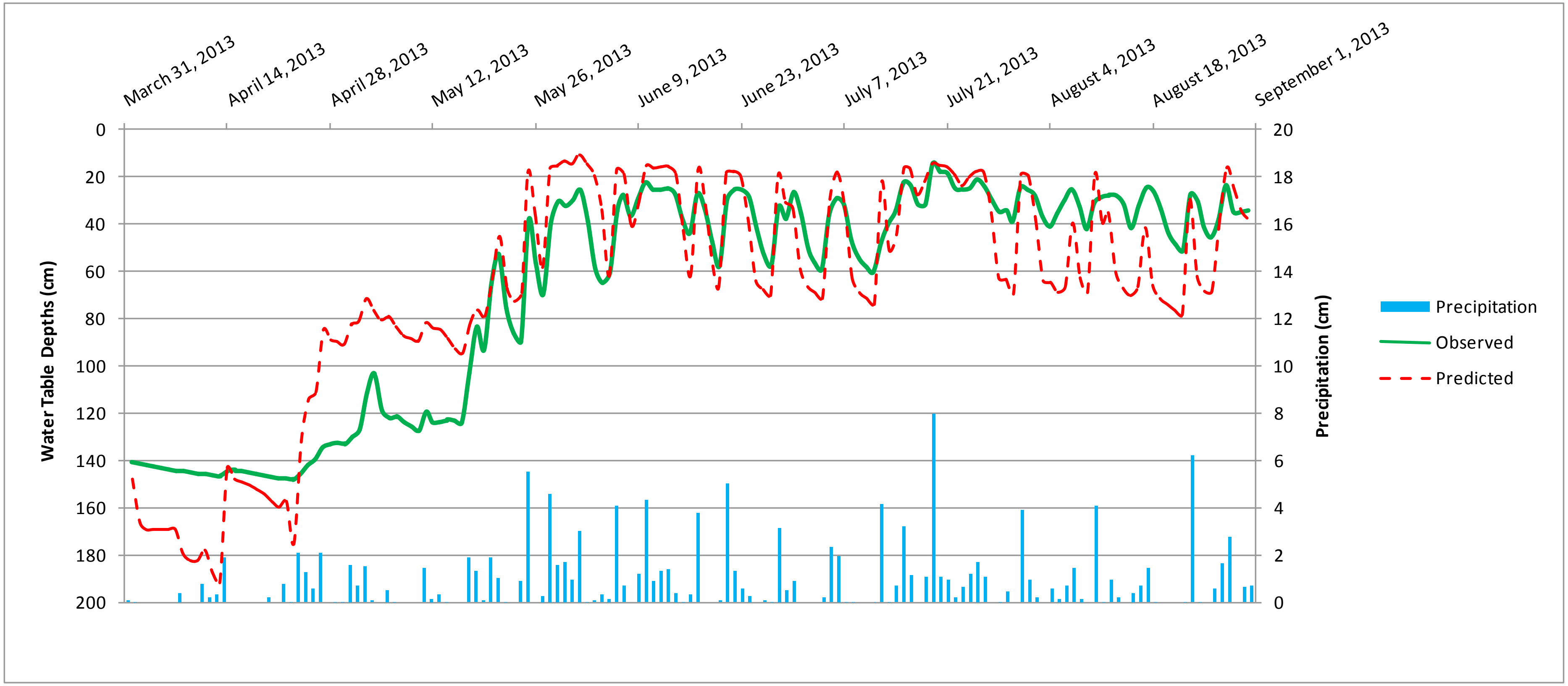


Figure 4.5Comparison of predicted and observed daily water table levels for the field during the calibration phase: April 1 to August 31, 2013.

Statistic	**Value**	**Assessment**
MAE (cm)	18.91	Acceptable
EF	0.76	Excellent
IoA	0.94	Excellent
PBIAS (%)	-0.07	Very Good

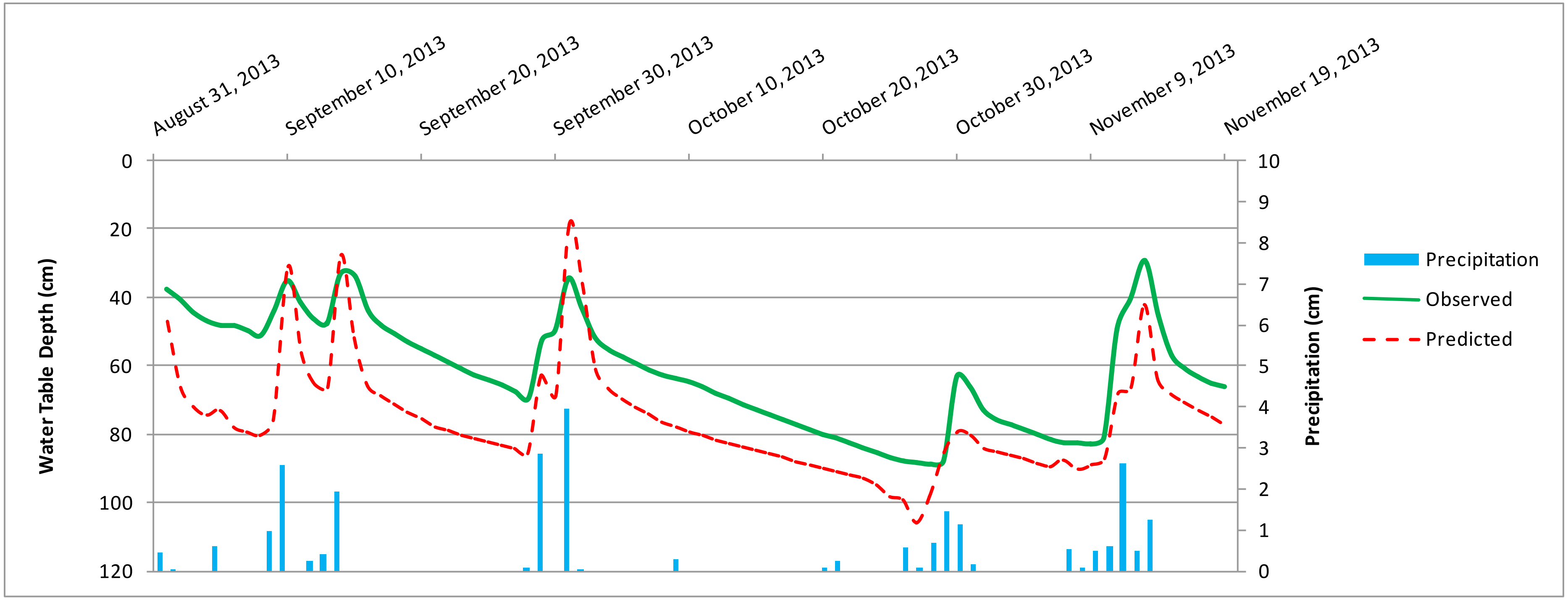


Figure 4.6 Comparison of predicted and observed daily water table levels for the field during the validation phase: September 1 to November 19, 2013.

Statistic	Value	Assessment
MAE (cm)	14.65	Good
EF	0.94	Excellent
IoA	0.99	Excellent
PBIAS (%)	-22.00	Satisfactory

A graphical comparison of the calibration curves shows that the two curves corresponded well during the months of May, June and July. However, there was a small disparity between the two for the month of August, which marks the gradual change into the dry season. This may be as a result of the montmorillonitic nature of the soil, which develops large cracks upon drying. Ultimately, infiltration may increase and this may lead to shallower water table levels as observed.

Nevertheless, the goodness of fit of the two curves in Figure 4.5 was assessed by the EF, IoA and PBIAS with values of 0.76, 0.94 and -0.07% respectively. The former two were assessed as excellent while the latter was assessed as very good indicating that the calibrated model was generally effective in predicting the water table levels. The figure also showed the water table response to daily precipitation as shallower water table depths closely followed the peaks of the precipitation bars.

For the validation phase, the predicted water table levels varied from 106 cm to 19 cm below the ground level as compared to observed values of 89 cm to 29 cm. The MAE was 14.65 cm and was assessed as good. This value was better compared to that of the calibration phase and was probably due to the range of water table depths not exceeding the 1.5 m field limit during this period. The goodness of fit also increased as compared to the calibration period with values of 0.94 and 0.99 for the EF and IoA respectively. This was shown in Figure 4.6 as the shape of the two curves (peaks and troughs) were more closely matched as compared to those for the calibration phase. The exception however, was the PBIAS at -22% which was still assessed as satisfactory. This may be explained by the continuous gap between the curves on the drawdown slopes, indicating a small overestimation bias by the model. As before, the water table response to daily precipitation closely followed the peaks of the precipitation bars. Moreover, the calibrated model could be deemed successful in predicting the water table levels for the heavy clay soils on sugarcane fields in Guyana.

Further examination of Figures 4.5 and 4.6 showed that in the peak of the wet season (June - July), the predicted water table level fluctuated between to 20 - 80 cm band of the soil profile. The observed water table level fluctuated in a slightly narrower band of 20 - 60 cm. Interestingly, in the long dry season, the predicted water table levels rarely fell below 1.0 m from the surface. This was very similar to the observed levels and it indicates how poor the drainage condition for that soil type is, in the field. This can affect production as shallow water table levels decreases the yields of sugarcane (Carter *et al.*, 1988 and Gayle *et al*., 1987). As previously stated, in 1990, Naraine showed that when the water level in the collector drains exceeded 0.9 m, as measured from the land surface, the sugarcane yields were significantly reduced (Ritzema, 1994). In addition, harvest commences in the dry season, and saturated heavy clays as a result of shallow water table levels reduces the trafficability of the soil and in effect the number of working days. This is of particular importance since the current focus by management is to mechanize the harvest process in the near future.

4.3 Simulations with DRAINMOD

The calibrated model was used to simulate the water balance of the field for different historical time periods. A simulation was carried out for the year 2013 using the field data as input. Further simulations were done to assess the drainage coefficient using the average year and the year with the wettest period during 1974 to 2012.

4.3.1 Analysis of long term climate data.

Precipitation

An analysis of precipitation records from the Georgetown meteorological station for the period from 1974 to 2012 revealed that 2008 was the wettest year with a total of 3365 mm (about 1.5 times greater than the annual average). However, January 2005 was the wettest month on record with a total of 1108 mm. This was almost five times greater than the average total for all January months during the period. Furthermore, maximum three consecutive monthly totals were computed from the data since this matches the duration of the long wet season (May-July). It was found that the period from December 2004 to February 2005 was the wettest 3-month period from the dataset with a total precipitation of 1717 mm (75% of the annual average). Figure 4.7 shows the distribution of the average monthly precipitation for the period. The monthly totals for the year 2005 were superimposed on the plot to show the deviations for that year.

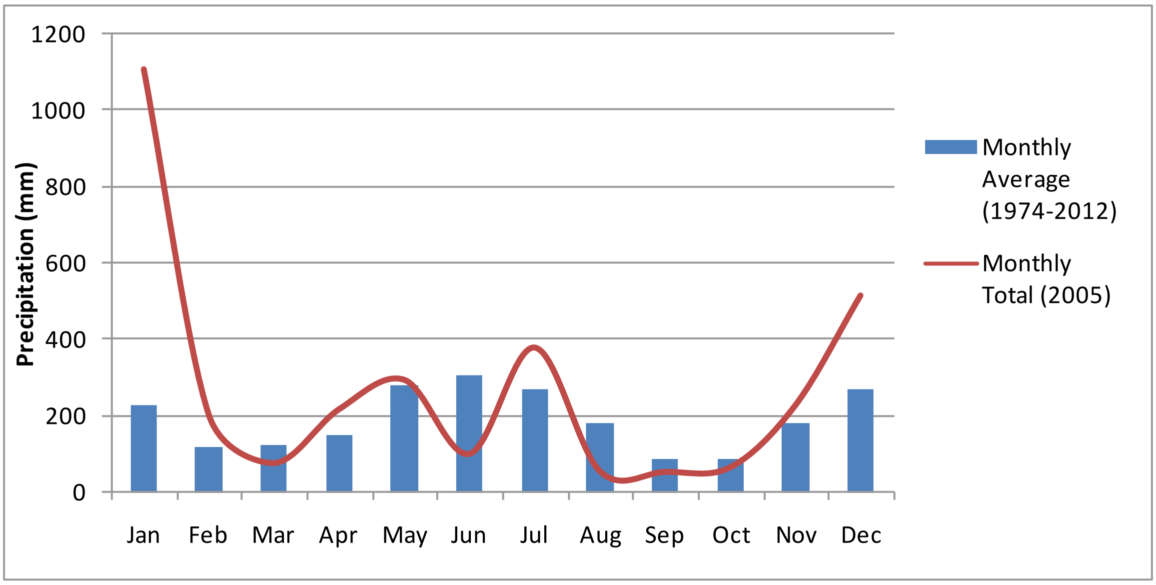


Figure 4.7: Average monthly totals of precipitation against actual monthly totals for 2005 at Georgetown.

The average annual rainfall for the period 1974-2012 was 2296 mm and the year 1999 was closest to this with an annual total of 2295 mm. Also, the total rainfall for 2013 at LBI was 2266 mm and hence 2013 could be considered as an average year. However, recall (from Figure 4.2) for the year 2013, the wet season was longer and precipitation was above average, while the short dry season (Feb -Apr) was below average. This demonstrates the seasonal variability in the distribution of the precipitation for an average year and therefore a cautious approach must be taken when analysing the annual totals. It is for this reason that the wettest period was used in the simulations rather than the wettest year.

<u>Temperature</u>

The daily maximum and minimum temperature record for Georgetown meteorological station was also analysed. For the period 1974 to 2012, the daily temperature varied from 18.5°C to 34.5°C giving a range of 16°C with an average of 27.1°C. However, the average of the daily maximum temperatures was 30.2°C, while the average daily minimum was 24.1°C. This gave a range of 6.1°C which is more characteristic of the daily temperature band for the coastal region.

For the average precipitation year (1999), the temperature ranged from 20.3°C to 33.7°C with an average of 27.3°C. Similarly, for the wet year (2005), the temperature ranged from 20.5°C to 33.9°C with an average of 27.7°C. Thus, very little variation exists between annual temperature fluctuations as reported from the earlier works of Ramraj (1996) and Bovolo *et al.* (2012).

4.3.2 Simulations for the average year and wettest period

The calibrated model was used to simulate the water balance for the years 1999 (average yr) and 2004-2005 (wettest period). The simulation outputs are given in Appendix A as tables showing the components of the water balance for the respective year.

The simulated water balance for the average year showed that the ET component (142.37 cm) was 62% of precipitation while the total field discharge accounted for 31%. These results were comparable to those from the measured water balance in this study. This may be because 2013 was also an average year of precipitation.

In contrast, the simulated water balance for 2005 had a lower ET component (139 cm) of 42% of precipitation, while the total field discharge was greater, at 48%, indicating that almost half of the precipitation was converted into runoff. This was expected as ET is lower than normal for wet years, and higher surface runoff is generated when heavy clays are saturated for prolonged periods.

4.3.3 Simulated water balance for 2013

Table 4.5 summarises the results of the simulated water balance for the year 2013. However, for a direct comparison to the measured field water balance, only the corresponding period from March 16 to November 26 was presented here. The results for the complete year of 2013 is given in Appendix A. The simulated field discharge was given as D+RO' (effective sub-surface drainage + surface runoff). This was computed by adjusting the sub-surface drainage component (D) by the correction factor 4/7 (section 3.5.6) before adding to the surface runoff component (RO). The change in soil moisture (ΔS_{sim}) was computed using equation 3.1 on a monthly basis using the simulated outputs.

The DRAINMOD simulated water balance was underestimating ET and overestimating sub-surface drainage. The total ET simulated for the period was 93.91 cm, which was 27% lower than that computed for the measured water balance. The combined totals for sub-surface drainage (43.64 cm) and surface runoff (27.87 cm) was 71.51 cm, which was 46.4% greater than the measured D+RO. However, after adjusting the simulated sub-surface drainage component, the D+RO' was 52.7 cm, representing a 7.9% increase over the field measurements.

The total net change in soil moisture for the simulated values was 5.68 cm, as compared to the measured value of 2.06 cm. However, there was a better agreement between the calculated net change in soil moisture (5.25 cm) and the simulated value. In general, the results indicate that the DRAINMOD simulated water balance was in good agreement with the measured field water balance for 2013.

Table 4.5: Summary of the simulated soil-water balance for 2013 using DRAINMOD.

Month	P[b] (cm)	ET[c] (cm)	D[d] (cm)	RO [e] (cm)	D+RO' [f] (cm)	ΔS_{sim}[g] (cm)
March[a]	5.54	4.54	0.00	0.00	0.00	1.00
April	11.04	8.50	0.00	0.00	0.00	2.54
May	28.52	13.77	4.21	4.17	6.58	6.37
June	34.38	15.30	15.23	6.19	14.89	-2.33
July	34.36	13.14	12.68	7.76	15.01	0.78
August	24.99	14.49	7.04	4.48	8.50	-1.02
September	10.23	9.35	2.00	0.13	1.27	-1.26
October	8.74	7.58	1.27	1.04	1.77	-1.15
November[a]	13.14	7.25	1.10	4.12	4.71	0.75
TOTAL	**170.94**	**93.91**	**43.64**	**27.87**	**52.73**	**5.68**

[a] Data set does not cover the entire month, [b] Precipitation, [c] Evapotranspiration, [d] Sub-surface Drainage, [e] Surface Runoff, [f] Effective D+RO, [g] Change in Soil Moisture.

4.3.4 Assessment of the design drainage coefficient

As previously discussed, the simulated daily field discharge (D+RO') was taken as the adjusted sub-surface drainage + surface runoff. This was assumed to be equal to the drainage rate of the field for a 1-day duration (DR1). The field discharges for two consecutive days were then summed together and divided by two to give the drainage rate for a 2-day duration (DR2). Likewise, the same was done for three consecutive days to find the drainage rate for a 3-day duration (DR3). The historical design drainage coefficients were based on storms of 3-day duration with a 1 in 2 yr return period (section 2.3.2), and hence DR3 was more suitable for comparison to assess the adequacy of the surface drains.

Figure 4.8 shows the drainage rates for the DR1, DR2, and DR3 duration for the year with average annual precipitation (1999). The graph also shows that the upper and lower limits of the historical design drainage coefficient (3.5 and 5.0 cm day^{-1}), as used for the design of surface drains and their complementing hydraulic structures on agricultural lands in Guyana. Similarly, Figure 4.9 shows the drainage rates for the wettest 3-month period from December 2004 to February 2005. The drainage rates for the complete year of 2005 is given in Appendix A.

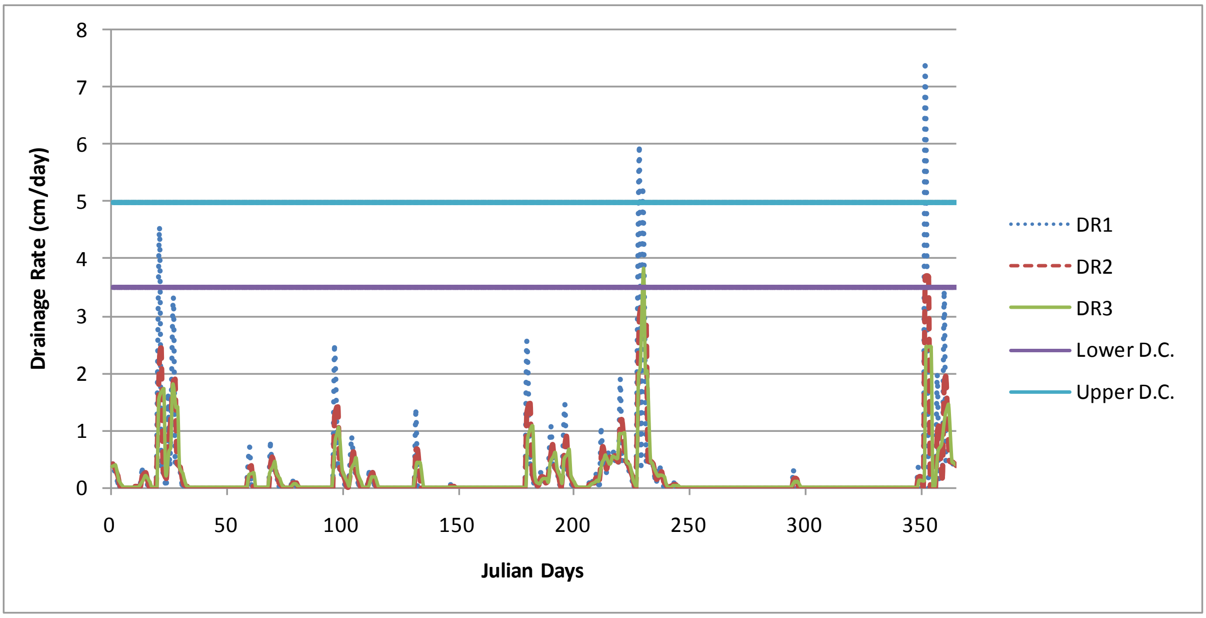


Figure 4.8: Drainage rates from the simulated daily field discharges for the average precipitation year (1999).

In Figure 4.8, for the average precipitation year of 1999, the simulated drainage rates seldom exceeded 2.5 cm day^{-1}. The lower limit of the design DC was exceeded once by DR3 during mid August of that year. However, DR1 exceeded the lower limit thrice and the upper limit twice during the wet seasons. Interestingly, the precipitation for this year had a return period of 1 in 2 yr, when the data was fitted to a normal distribution function. Although this equates to the return period of the design storm, it does not imply that the design drainage coefficient is based on an average year of precipitation. Typically, drainage systems for agricultural lands are designed for a 1 in 5 yr design storm. Therefore, the design DC can be assessed as being adequate for surface drains during an average year.

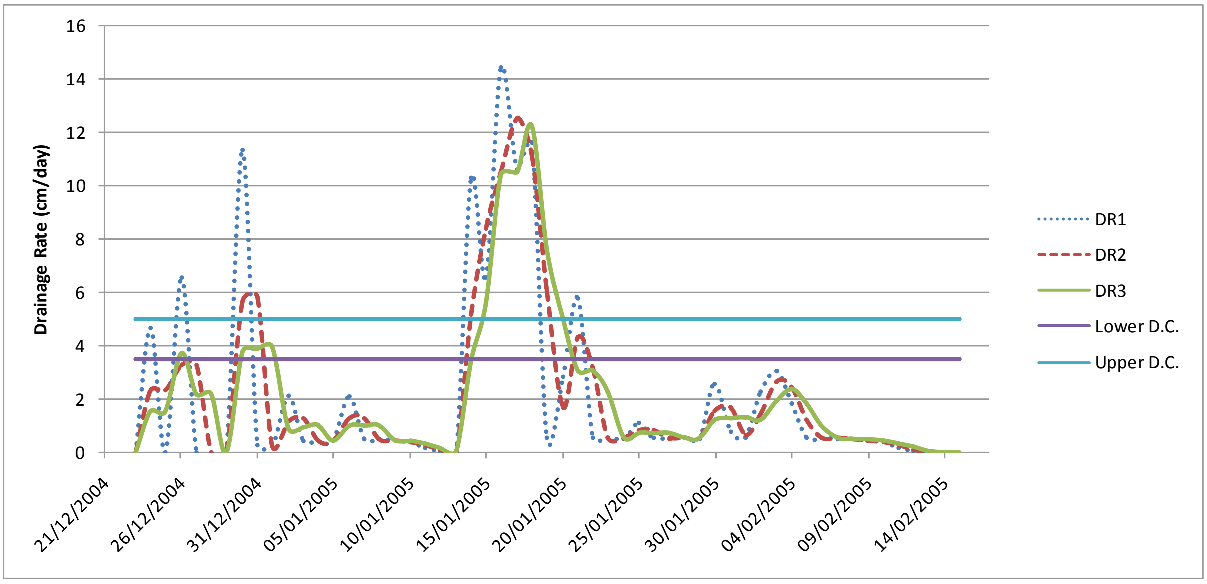


Figure 4.9: Drainage rates from the simulated daily field discharges for the wettest 3-month period (December 2004 - February 2005).

In contrast, Figure 4.9 shows that the simulated drainage rate for DR3 peaked at 12 cm day^{-1} during January 2005. This was three times higher than the lower limit of the design DC and it was exceeded for about seven consecutive days. The lower DC was also exceeded twice in late December 2004 by the drainage rate for DR3. Altogether, the design DC was exceeded several times for prolonged periods during this critical wet season. Given the extreme nature of such events, this wet period was fitted to the Gumbel Type 1 distribution function.

This was done in several configurations to compute a range of return periods. Firstly, as the maximum 1-month totals, where the return period for January 2005 was found to be 1 in 356 yr. Secondly, as 3-month totals for all Dec-Jan-Feb months during the 1974 to 2012 period. This resulted in a return period of 1 in 51.6 yr. The third configuration was the maximum 3-month totals for all months giving a return period of 1 in 98.1 yr. Table 4.6 summarises the return periods for the different configurations of data fitted to the Gumbel distribution.

Table 4.6: Summary of the return periods for the three configurations fitted to the Gumbel distribution.

Configuration	**P[a] (mm)**	**T_r[b] (yr)**		**Remarks**
		Rank	**Gumbel**	
Max 1-month	1108.2	40.0	355.5	Jan 2005 (maximum)
	459.6	2.9	2.3	Jun 1976 (average)
3-month[c]	1716.5	40.0	51.6	Dec 2004 - Feb 2005 (maximum)
	673.3	2.6	2.3	Dec - Feb (average)
Max 3-month	1716.5	40.0	98.1	Dec 2004 - Feb 2005 (maximum)
	1008.2	2.1	2.3	May - Jun (average)

[a] Precipitation, [b] Return Period, [c] From December to February only.

The values from Table 4.6 confirms that the flood events of the wettest period in 2004-05 was extreme. The shortest return period of 1 in 52 yr is largely out of the range of the more commonly used 1 in 5 yr return period for designing drainage systems on agricultural fields. It can therefore be concluded from the DRAINMOD simulations that the design drainage coefficient are adequate for surface drainage systems for sugarcane fields in Guyana.

In closing this chapter, it is worth noting that in addition to the evaluation of the design drainage coefficient, the actual performance of surface drainage systems in Guyana depends on other factors such as surface storage, canal conveyance and the tidal conditions at the discharge sluices. These can be factored into studies with greater scope, where the economic considerations between cost and benefit for varying degrees of flood risk can also be evaluated. It is also important to note that with any drainage system, proactive maintenance programmes are central to ensure efficiency and effectiveness in functionality, and these should also be part of the evaluation.

CHAPTER 5.0 CONCLUSIONS AND RECOMMENDATIONS

Based on the research conducted, the following conclusions are drawn:

5.1 Field water balance

A 4.2 ha sugarcane field at LBI sugar estate in Guyana was instrumented to measure the components of the soil-water balance. This was done for the period from 16 March to 26 November, 2013. The measured components were i) precipitation (170.8 cm), ii) crop evapotranspiration (129.1 cm), iii) combined sub-surface drainage + surface runoff (48.8 cm), and iv) the net change in soil moisture (2.06 cm). By comparison, a water balance equation was used to calculate the net change in soil moisture from the precipitation and crop ET measurements, giving a value of 5.25 cm. The difference in values may be attributed to the lack of continuous measured soil moisture data, as we were only able to undertake gravimetric soil moisture measurements every 27 days on average.

The ET component accounted for about 76% of the precipitation for the study period. This was in good agreement with other water balance studies for both rainfed and irrigated sugarcane fields globally, as several studies gave ET components varying from 64% to 87% of the local precipitation and/or irrigation.

Similarly, in this study, the combined sub-surface drainage + surface runoff (total field discharge) was about 28% of the precipitation. However, this component was marginally higher than published values of 15% and 20% from studies in other parts of the world. This may be as result of differences in the soil physical properties, as more surface runoff can be expected from the heavy clays of Guyana.

5.2. DRAINMOD simulations

DRAINMOD was used to simulate the field water balance, and the results compared the field measurements. The model was calibrated and validated by comparing observed water table levels from three wells in the field, against predicted water levels from the model. The calibration was done for the wet season spanning from April to August, and the model performed favourably with an EF of 0.76, IoA of 0.94, MAE of 18.91 cm and PBIAS of -0.07%.

The model validation was done for the dry season spanning from September to November. Similarly, the results showed good agreement between predicted and observed water table levels with an EF of 0.94, IoA of 0.99, MAE of 14.65 cm and PBIAS of -22%.

These values are well within the ranges of values reported from other studies with DRAINMOD, inclusive of those for sugarcane fields. 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 predict drainage and runoff, and water table levels for long term climatic evaluations. The year 1999 was found to represent an average year of precipitation, while the wettest season (3-month period) occurred between December2004 and February2005.

This extremely wet period had a total precipitation of 1717 mm (75% of the annual average), of which 1103 mm occurred in January, 2005. Simulations were run for 1999 and the 2004-2005 wet years.

The simulated water balance for 1999 showed that the ET component was 62% of precipitation while the total field discharge accounted for 31%. These results were comparable to those from the measured water balance. This may be because 2013 was an average year of precipitation.

In contrast, the simulated water balance for 2005 had a lower ET component of 42% of precipitation, while the total field discharge was greater, at 48%, indicating that almost half of the precipitation was converted into runoff. This was expected as ET is lower than normal for wet years, and higher surface runoff is generated when heavy clays are saturated for prolonged periods.

Finally, the simulation results for 2013 showed that the total ET simulated for the period March 16 to November 26 was 93.91 cm, which was 27% lower than that computed for the measured water balance. The total field discharge was 52.7 cm, representing a 7.9%

increase over the field measurements. The total net change in soil moisture for the simulated values was 5.68 cm, as compared to the measured value of 2.06 cm. However, there was a better agreement between the calculated net change in soil moisture (5.25 cm) and the simulated value. In general, the results indicate that the DRAINMOD simulated water balance was in good agreement with the measured field water balance for 2013.

5.3. Assessment of the historical design drainage coefficient

The daily total field discharge from the DRAINMOD simulations were used to compute the simulated drainage rates, which were then compared to historical design drainage coefficients of 3.5 to 5.0 cm day^{-1} for agriculture in Guyana. These design coefficients were derived from frequency analysis of historical precipitation, and are given for a 3-day storm with a 1 in 2 yr return period.

For the average precipitation year of 1999, the simulated drainage rates seldom exceeded 2.5 cm day^{-1}, with a peak of 3.9 cm day^{-1} occurring during mid August of that year. Interestingly, the precipitation for this year had a return period of 1 in 2 yr, when the data was fitted to a normal distribution function. Although this equates to the return period of the design storm, it does not imply that the design drainage coefficient is based on an average year of precipitation. Typically, drainage systems for agricultural lands are designed for a 1 in 5 yr design storm.

For the wettest period in 2004-05, the simulated drainage rate was 12 cm day^{-1} during January 2005, exceeding the upper limit of the design drainage coefficient. However, the precipitation for this wet season had a return period of 1 in 52 yr, as determined by fitting the data to the Gumbel Type 1 distribution.

This indicates that the 2005 event was extreme, and it falls outside the range of return periods used for designing drainage systems of agricultural lands. It can therefore be concluded from the DRAINMOD simulations that the design drainage coefficients are adequate for surface drainage systems for sugarcane fields in Guyana. .

5.4 Recommendations for Further Research

Based on the work presented in this thesis, the following are recommended for further investigation:

1) Expanding the water balance study to cover a wider range of climatic conditions. Continuous field measurements using the same methodology outlined in this thesis should be taken over several years to include for hydrological conditions in a wet and dry year. This will allow for further calibration and validation of DRAINMOD for the application to sugarcane fields in Guyana;
2) Evaluating several types of layout for a surface drainage system that is suitable for sugarcane fields adapting a mechanized harvesting process. This is critical for the local sugarcane industry as shortages in the labour supply has affected harvesting which is traditionally based on intensive manual labour;
3) Evaluating the effects of drainage on sugarcane yields in Guyana for different water management practices. This can be coupled with the second recommendation as listed above, to focus on sugarcane yields against various surface drainage system layouts;
4) Modelling nutrient and pesticide transport on agricultural lands in Guyana's coastal region. This can result in better management practices for fertiliser and pesticide application, and to mitigate environmental hazards as a result of toxic chemicals being leached into drainage canals;
5) Modelling the effects of climate change on the drainage and hydrology of agricultural lands in Guyana's coastal region. Predictions of daily temperature and precipitation for various future climate scenarios can be modelled and used to simulate the hydrological water balance of agricultural lands. The effectiveness of the current drainage criteria can then be tested and evaluated under future conditions.

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APPENDIX A: Simulation Output

Table A1: Simulated soil-water balance for 1999.

Month	P[a] (cm)	ET[b] (cm)	D[c] (cm)	RO [d] (cm)	D+RO' [e] (cm)
January	27.33	13.44	7.98	8.86	13.42
February	8.13	9.93	0.06	0.00	0.03
March	13.84	10.64	2.04	1.38	2.55
April	19.58	13.01	4.79	3.11	5.85
May	19.00	15.99	0.00	1.39	1.39
June	21.41	14.94	0.95	2.44	2.98
July	23.67	12.96	6.51	3.17	6.89
August	39.88	14.33	15.17	12.62	21.29
September	4.37	14.48	0.04	0.00	0.02
October	11.35	12.61	0.00	0.31	0.31
November	4.04	4.86	0.00	0.00	0.00
December	36.8	5.18	5.28	12.67	15.69
TOTAL	**229.4**	**142.37**	**42.82**	**45.95**	**70.42**

[a] Precipitation, [b] Evapotranspiration, [c] Sub-surface Drainage, [d] Surface Runoff, [e] Effective D+RO.

Table A2: Simulated soil-water balance for December 2004 and Year 2005.

Month	P[a] (cm)	ET[b] (cm)	D[c] (cm)	RO [d] (cm)	D+RO' [e] (cm)
December[f]	40.46	2.72	0.67	22.53	22.91
January	110.82	13.41	24.06	65.26	79.01
February	20.35	10.79	12.98	5.44	12.86
March	7.85	7.8	0.04	1.50	1.52
April	21.97	11.79	3.83	4.78	6.97
May	29.57	16.63	7.28	4.99	9.15
June	10.29	17.13	1.43	0.00	0.82
July	38.00	13.61	5.42	9.98	13.08
August	5.66	16.03	1.05	0.00	0.60
September	5.59	8.53	0.00	0.00	0.00
October	6.73	6.08	0.00	0.65	0.65
November	22.94	7.87	0.00	11.29	11.29
December	51.64	9.34	16.83	13.68	23.30
TOTAL[g]	**331.41**	**139.01**	**72.92**	**117.57**	**159.24**

[a] Precipitation, [b] Evapotranspiration, [c] Sub-surface Drainage, [d] Surface Runoff, [e] Effective D+RO,

[f] for Year 2004, [g] Total for Year 2005 only.

Table A3: Simulated soil-water balance for 2013.

Month	P[a] (cm)	ET[b] (cm)	D[c] (cm)	RO [d] (cm)	D+RO' [e] (cm)
January	6.96	6.06	0.00	0.00	0.00
February	6.27	8.31	0.00	0.00	0.00
March	6.55	5.56	0.00	0.00	0.00
April	11.04	8.50	0.00	0.00	0.00
May	28.52	13.77	4.21	4.17	6.58
June	34.38	15.30	15.23	6.19	14.89
July	34.36	13.14	12.68	7.76	15.00
August	24.99	14.49	7.04	4.48	8.50
September	10.23	9.35	2.00	0.13	1.27
October	8.74	7.58	1.27	1.04	1.77
November	22.1	11.41	1.22	6.45	7.15
December	32.46	9.79	7.44	5.93	10.18
TOTAL	**226.61**	**123.26**	**51.09**	**36.15**	**65.34**

[a] Precipitation, [b] Evapotranspiration, [c] Sub-surface Drainage, [d] Surface Runoff, [e] Effective D+RO.

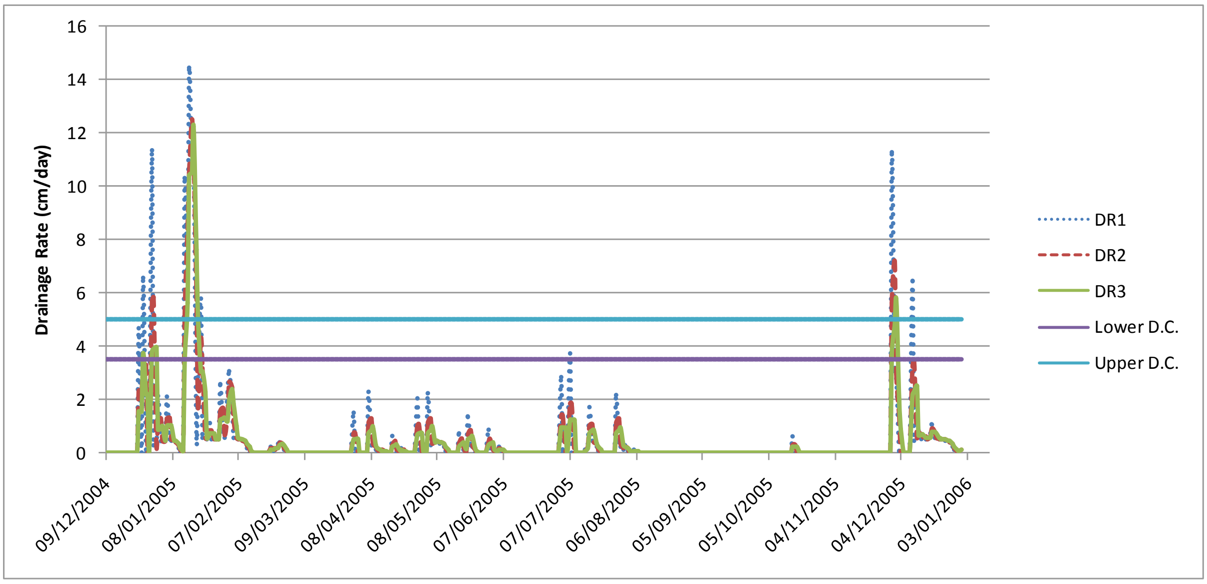

Figure A4: Drainage rates from the simulated daily field discharges for December 2004 - December 2005.

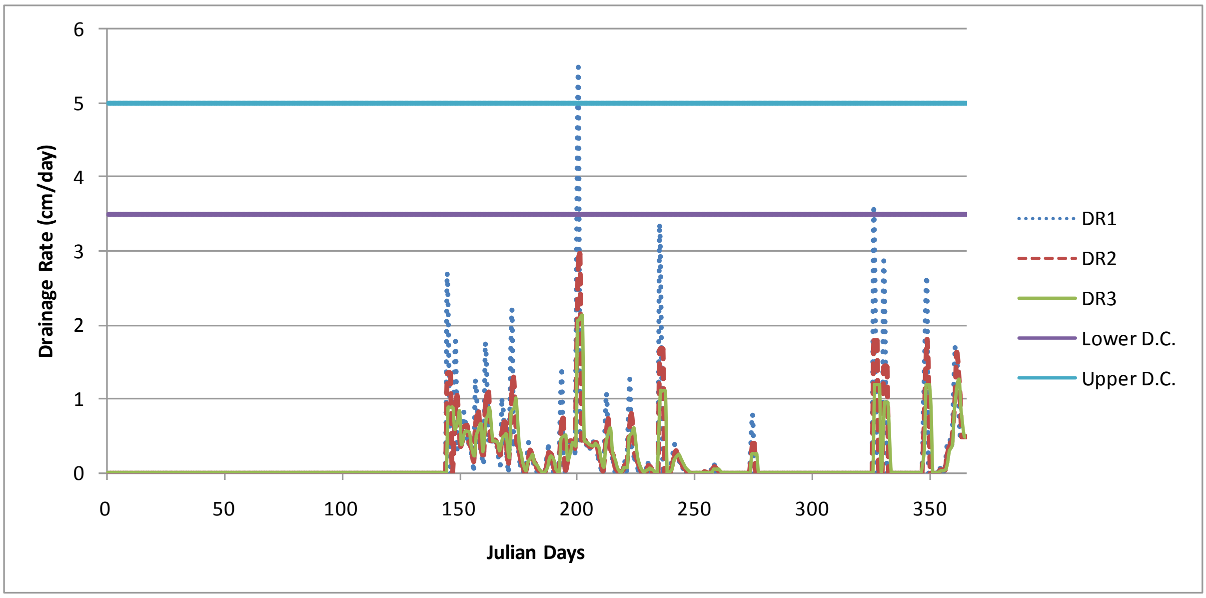

Figure A5: Drainage rates from the simulated daily field discharges for the Year 2013.

APPENDIX B: Calibration Curves

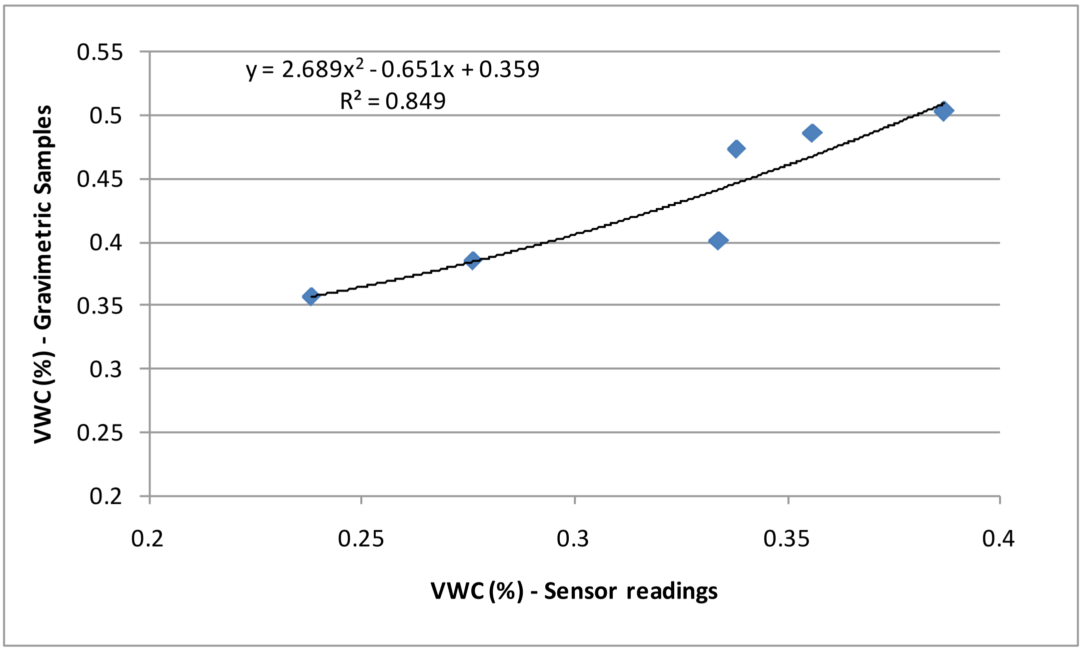

Figure B1: Calibration curve for the 10HS soil moisture smart sensors for Layer 1 (0-22 cm).
Note: VWC is the volumetric water content of the soil

The transducers were calibrated for an offset value to give the best-fit between observed and computed values.

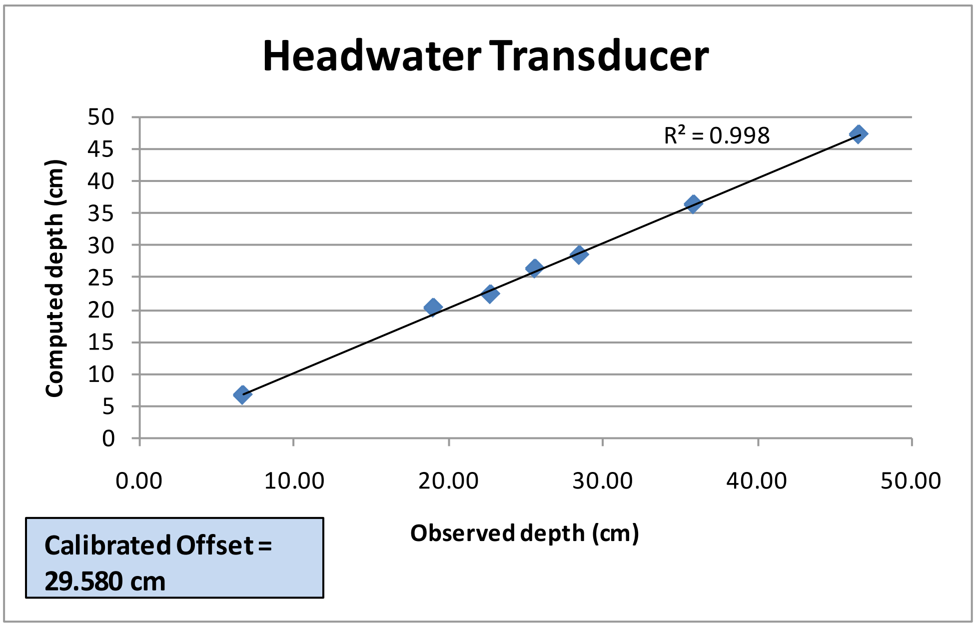

Figure B2: Comparison of observed vs. computed depth at the 45cm dia. HDPE pipe culvert (Headwater) for the KPSI 700 pressure transducer.

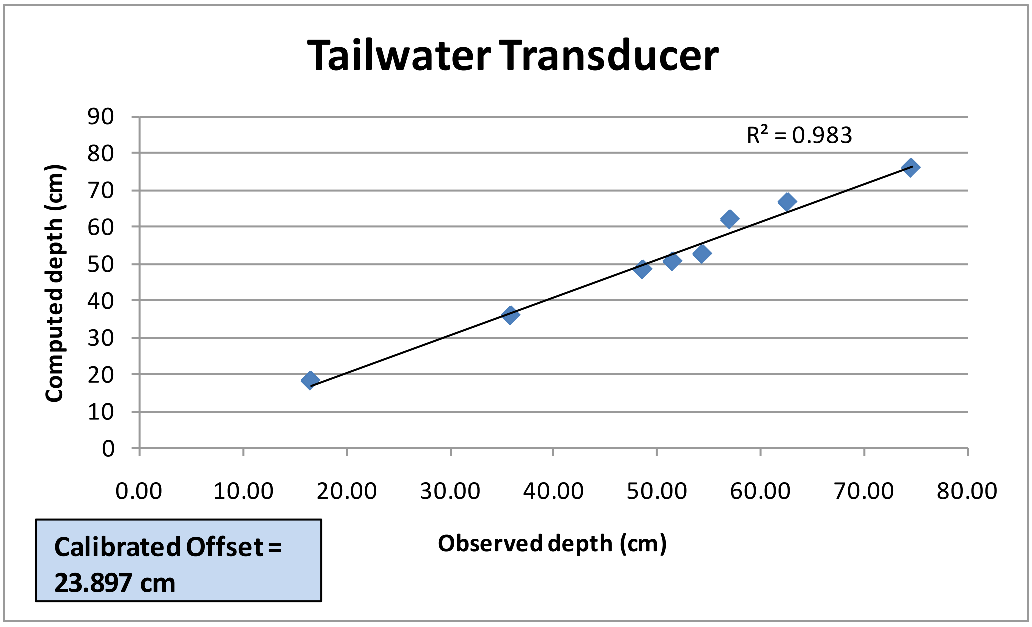

Figure B3: Comparison of observed vs. computed depth at the 45cm dia. HDPE pipe culvert (Tailwater) for the KPSI 700 pressure transducer.

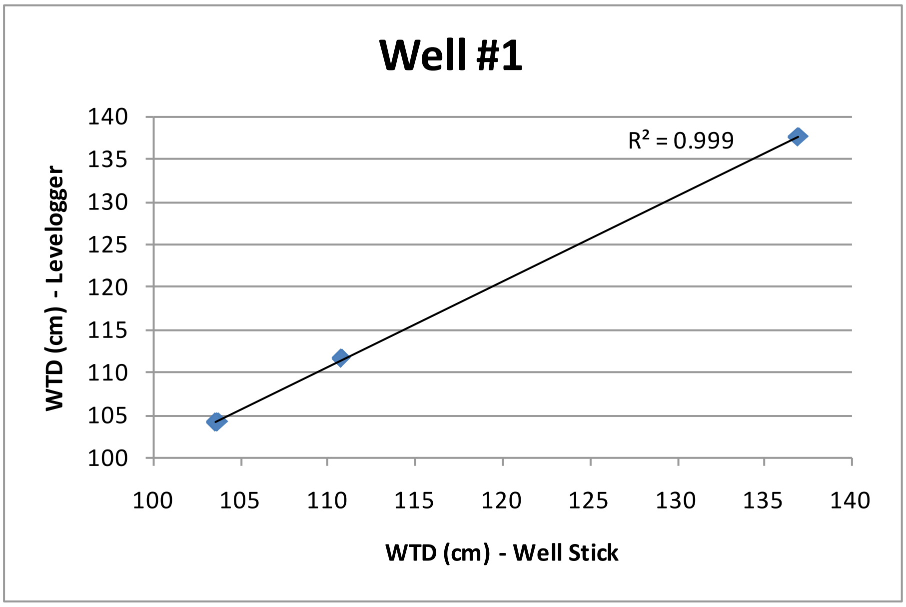

Figure B4: Comparison of well stick vs. Solinst levelogger water table depths for well #1.

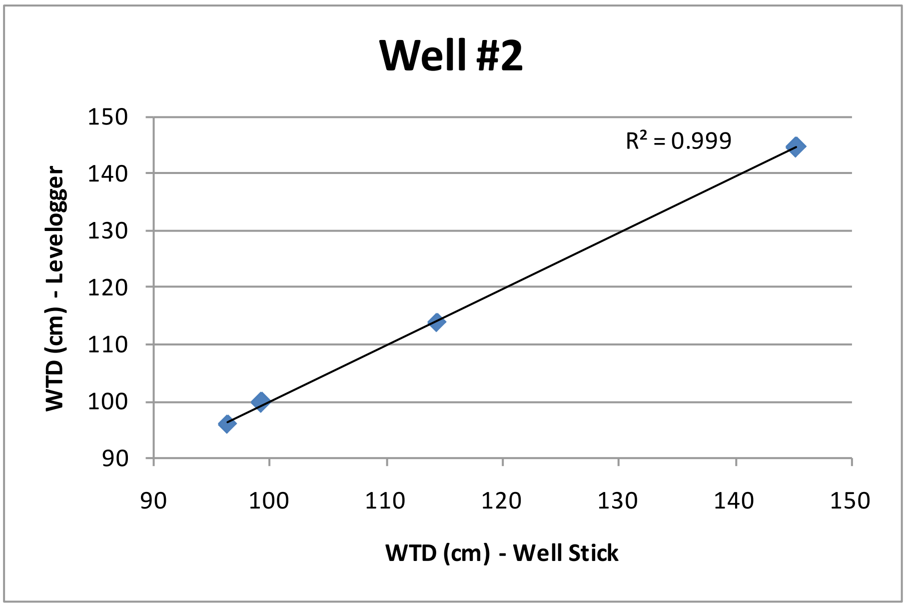

Figure B5: Comparison of well stick vs. Solinst levelogger water table depths for well #2.

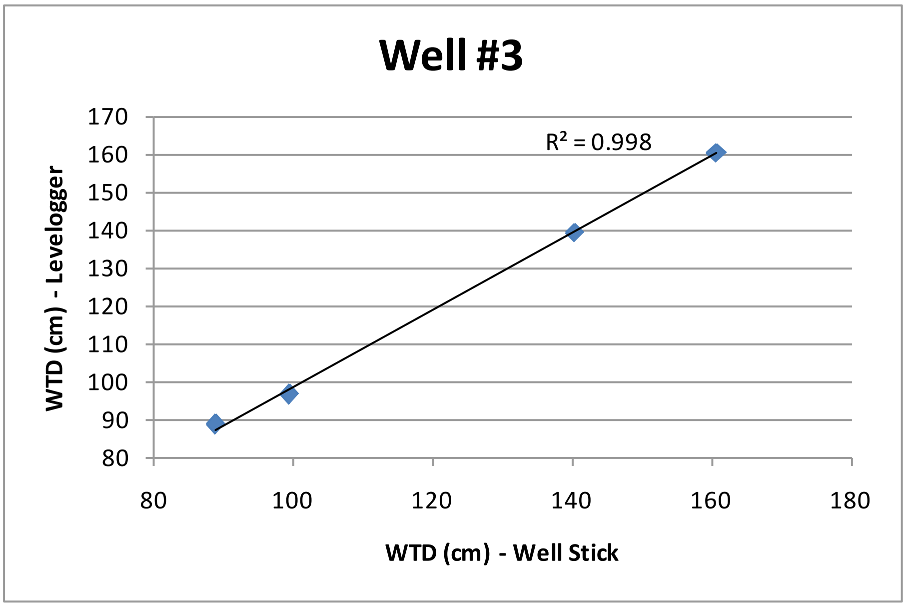

Figure B6: Comparison of well stick vs. Solinst levelogger water table depths for well #3.

APPENDIX C: Culvert Hydraulics Formulae & Curves

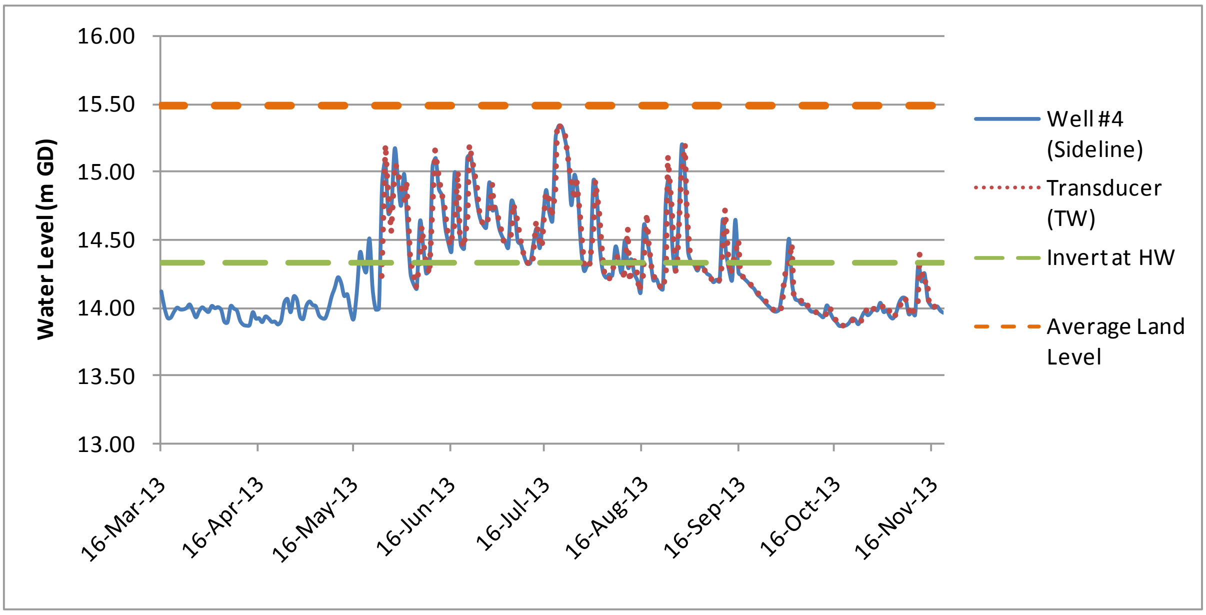

Figure C1: Comparison of the water level in the Sideline drain (Well #4) and the tailwater elevation at the HDPE pipe culvert. Note: The invert level at the headwater was 14.331 m GD and all water levels above this indicates either submerged discharge or backflow.

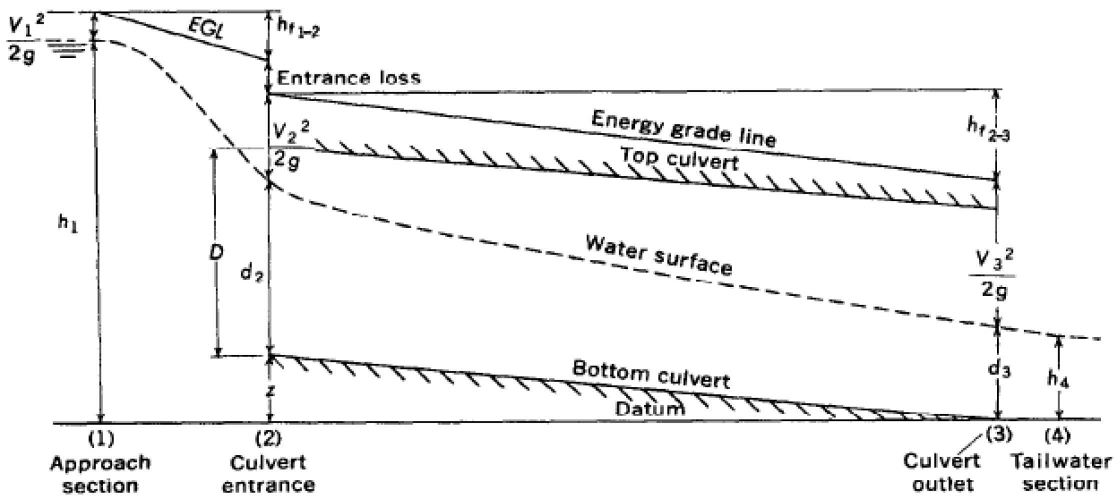

Figure C2: Definition sketch of culvert flow according to the USGS (adapted from Bodhaine, 1968).

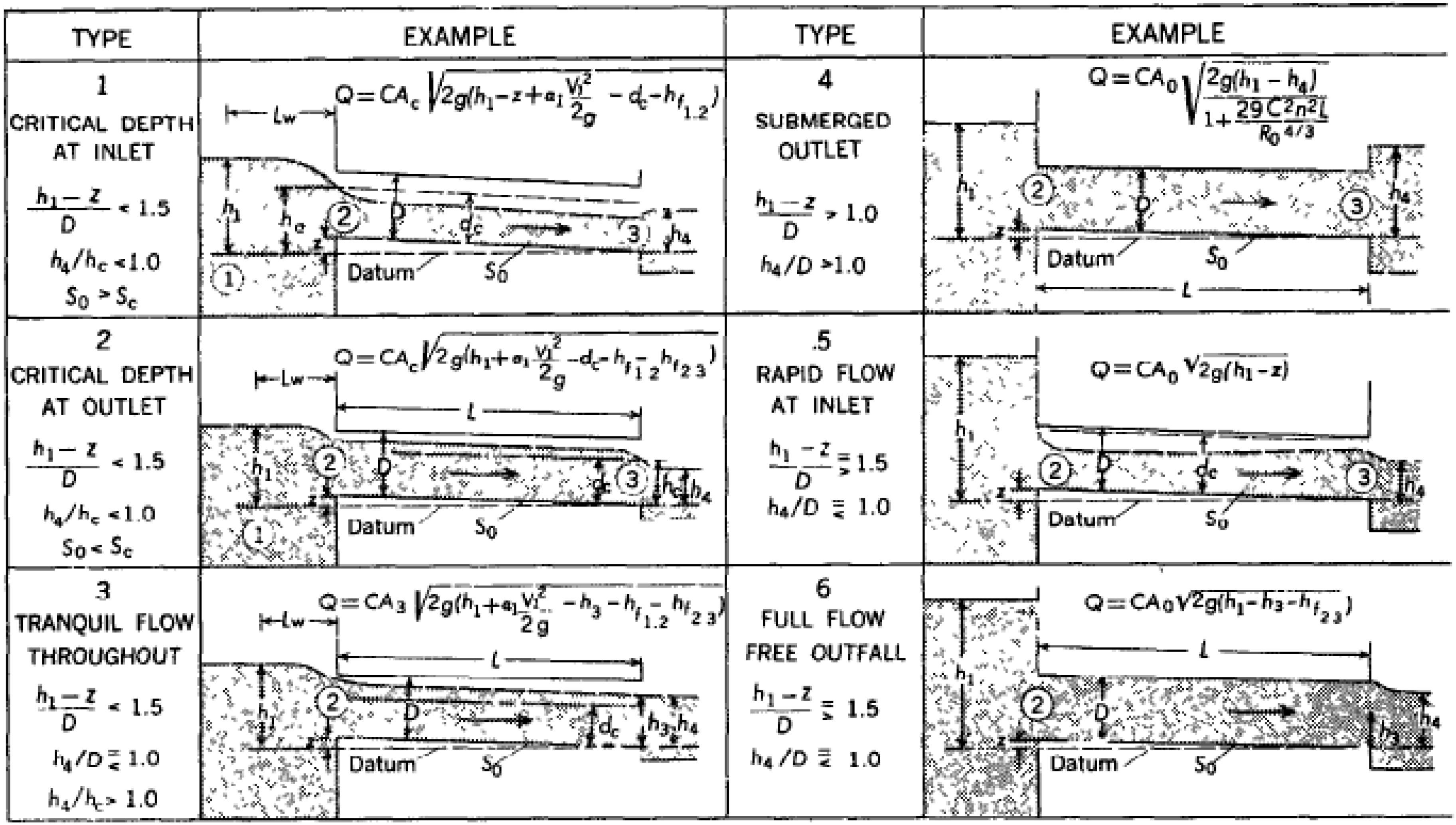

Figure C3: USGS classification of culvert flow based on hydraulic conditions (adapted from Bodhaine, 1968).

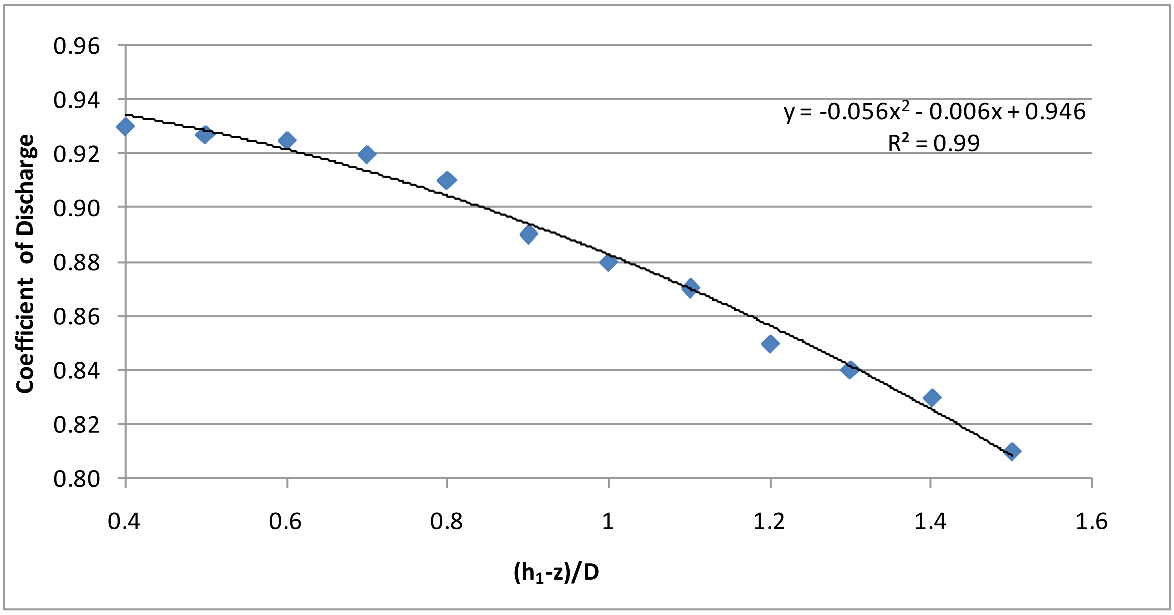

Figure C4: Coefficient of Discharge function for Type 1, 2 and 3 flows (reproduced from Bodhaine, 1968).

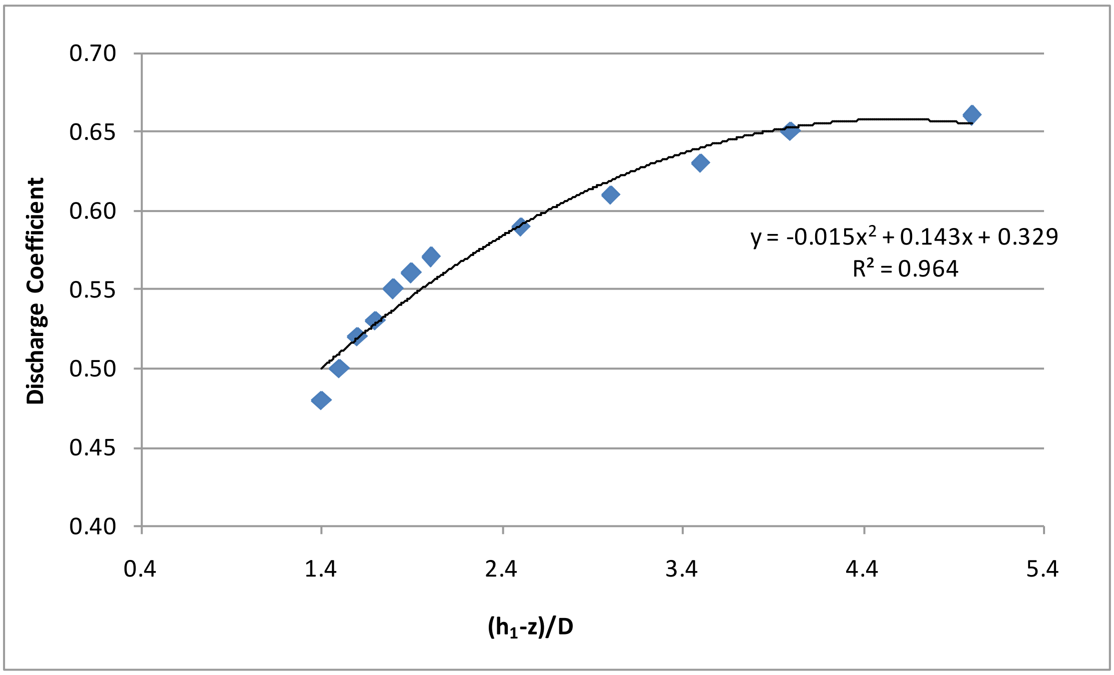

Figure C5: Coefficient of Discharge function for Type 5 flows (reproduced from Bodhaine, 1968).

The coefficient of discharge for Type 4 flows was constant (0.81) for all ratios of h_1-z/D. None of the recorded flows were classified as Type 2 or Type 6 flows. All computations were done in English (Imperial) Units.

APPENDIX D: Soil Properties and Characteristics

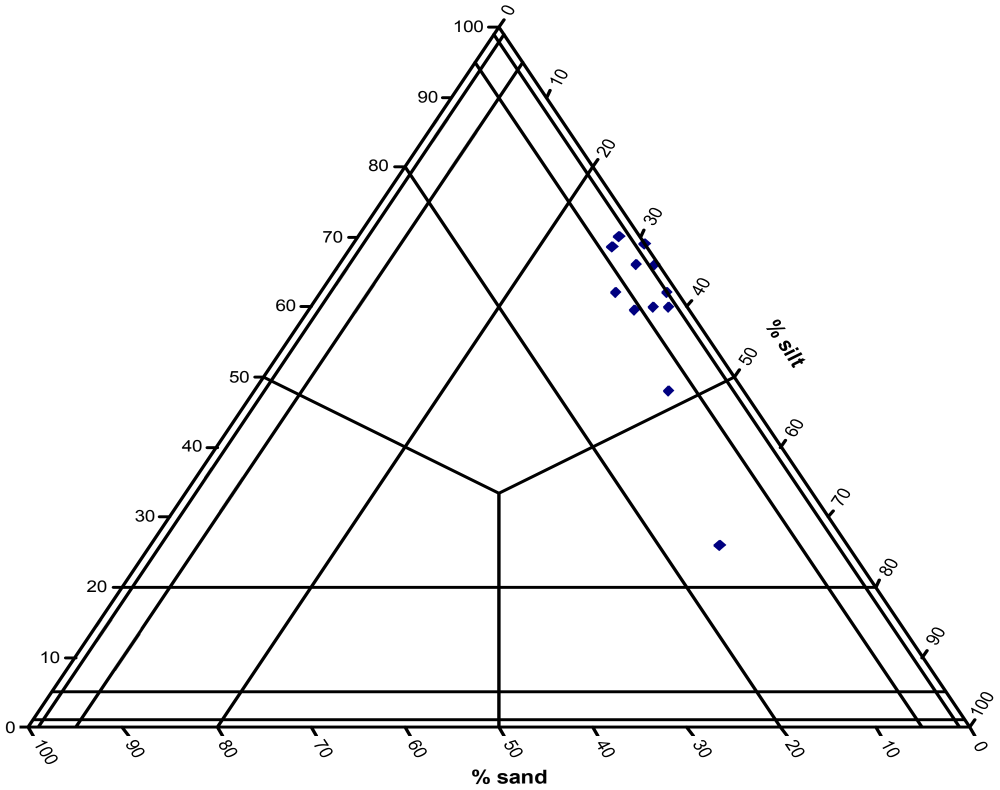

Figure D1: Plot of the particle size distribution on the USDA Soil Textural Triangle for all 12 samples.

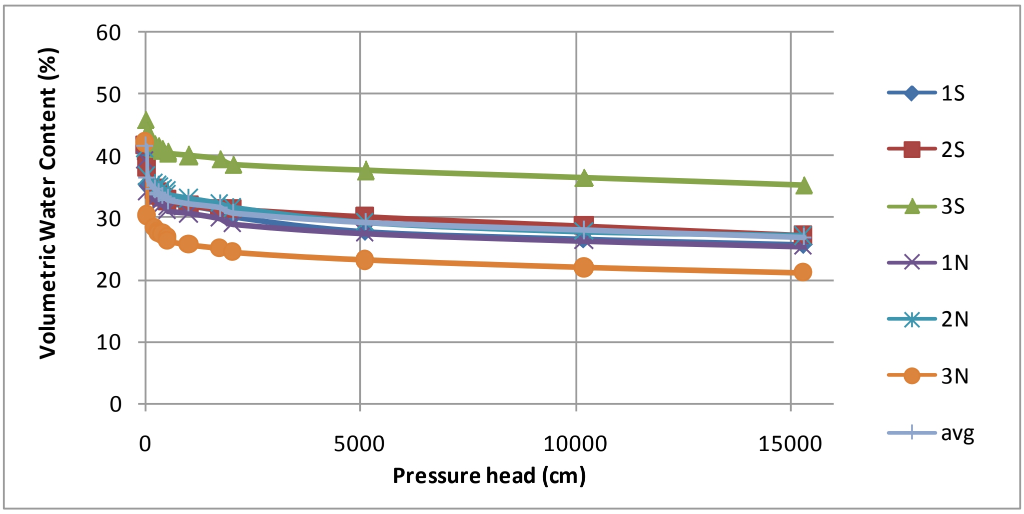

Figure D2: Soil Water Characteristic Curve of Layer 1 (0-22 cm) for all 6 samples.

Note: N - samples taken north of the internal field drain

S - samples taken south of the internal field drain

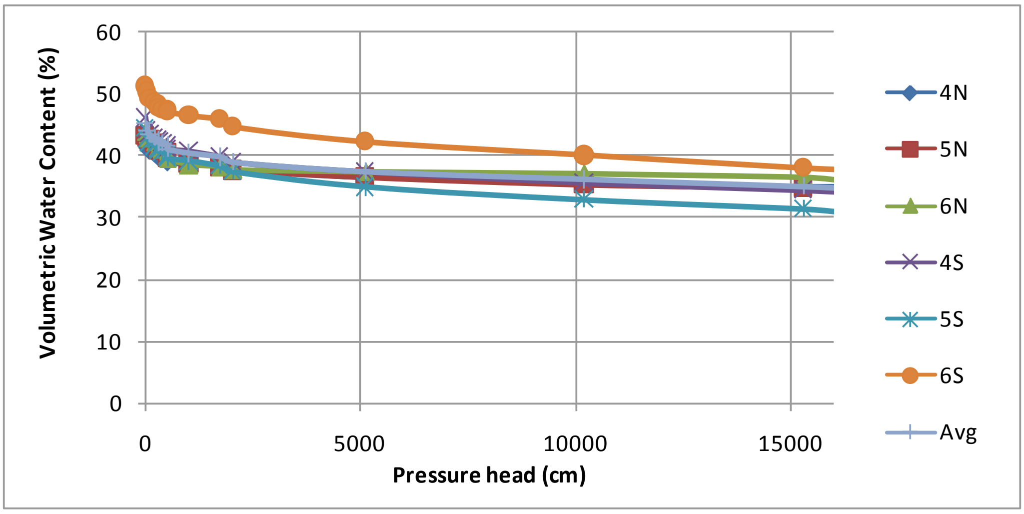

Figure D3: Soil Water Characteristic Curve of Layer 2 (22-65 cm) for all 6 samples.

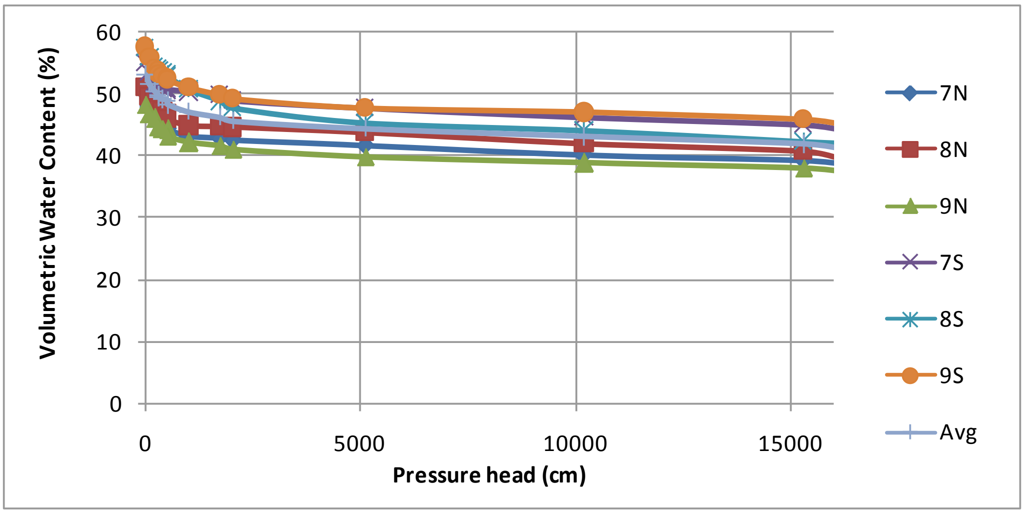

Figure D4: Soil Water Characteristic Curve of Layer 3 (65-100 cm) for all 6 samples.

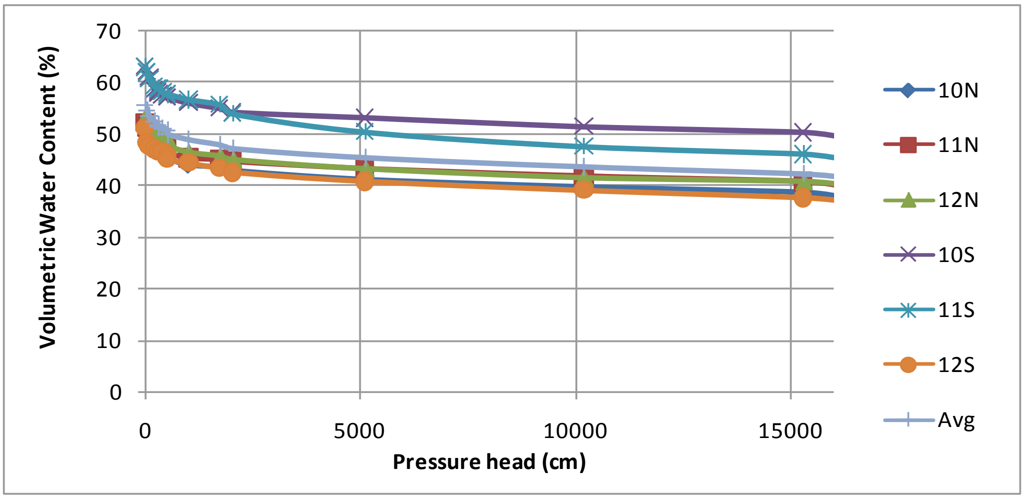

Figure D5: Soil Water Characteristic Curve of Layer 4 (100-141 cm) for all 6 samples.