# DROUGHT ASSESSMENT TOOLS FOR AGRICULTURAL WATER MANAGEMENT IN JAMAICA

by

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# ABSTRACT

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**Drought assessment tools for agricultural water management in Jamaica**

Increasing urban development, in addition to changing climatic conditions, are just a few of the factors negatively impacting Jamaica's water resources. Therefore, conceptual tools are required for the management of water resources during water scarce conditions. Such tools include drought indices, irrigation requirement guidelines and computer simulation models for irrigation planning.

Monthly irrigation demands were calculated for three sites in Jamaica: Savanna-la-mar in the parish of Westmoreland, Beckford Kraal in the parish of Clarendon, and Serge Island in the parish of St. Thomas. This was done using simulated monthly available soil moisture values averaged over a 30 year period, for both vegetables and sugarcane. The greatest irrigation demands were found to be in the dry period of January to April, as well as July to August for Savanna-la-mar and Beckford Kraal. Serge Island, however, needs irrigation throughout the year.

Two drought indices, the Standardized Precipitation Index (SPI) and the Normalized Difference Vegetation Index (NDVI), were used for the study sites. Both indices were correlated to simulated monthly available soil moisture. It was found that the relationship between each index and soil moisture varies from month to month, with drier months resulting in better correlations than wet months. Predicted available soil moisture values have been calculated for the different SPI categories. It was found that available soil moisture is lowest in the months of March and April. In addition, irrigation requirements were determined for the Moderately Dry and Severely Dry SPI categories of drought in the drier months of the year, for the three study locations, for both vegetables and sugarcane.

SWAT was used to model the hydrology of the Rio Nuevo watershed in St. Mary, Jamaica. SWAT was calibrated and validated using measured streamflow data from the period 2002 to 2007, and achieved satisfactory model performance, with a Nash-Sutcliffe Efficiency of 0.78 for calibration and 0.52 for validation. The SWAT model results were used to determine streamflow capacity for irrigation demands in an agricultural sub-basin of the watershed, and it was found that during the drought year of 2000, there was not enough streamflow to meet irrigation demands of January and March.

## RÉSUMÉ

Maîtrise en Science **Johanna Richards** Génie en Bio-ressource

**Outils d'évaluation des sécheresses pour la gestion des eaux de l'agriculture en Jamaïque**

L'augmentation du développement urbain et les changements climatiques ne sont que deux des multiples facteurs ayant un impact néfaste sur les ressources hydriques de la Jamaïque. A cet effet, des outils conceptuels sont nécessaires à la gestion des eaux en période de sécheresse. De tels outils sont par exemple les indices de sécheresse, les guides d'irrigation et les planificateurs d'irrigation (par exemple le SWAT, Soil and Water Assessment Tool).

Les demandes nettes en irrigation de trois sites jamaïcains ont été calculées: Savanna-la-mar (Westmoreland), Beckford Kraal (Clarendon) et Serge Island (St-Thomas). Ces calculs sont basés sur les moyennes des conditions mensuelles d'humidité disponible des soles, échelonnées sur une période de trente ans et en provenance de sites où sont produits des légumes et de la canne à sucre. La période sèche de janvier à avril connait les plus grandes demandes d'irrigation. La période de juillet à août pour les sites de Savanna-la-mar et Beckford Kraal connait aussi des demandes importantes. Le site de Serge Island a besoin d'irrigation tout au long de l'année.

Deux indices de sécheresse ont été développés pour les sites d'études : l'Indice de Précipitation Standardisé (IPS) et l'Indice de Végétation de Différence Normalisée (IVDN). Tous deux ont été corrélés afin de simuler l'humidité mensuelle disponible des soles. Les résultats démontrent que la relation entre chaque index et l'humidité des soles varie de mois en mois, les mois plus secs offrant de meilleures corrélations que les mois plus humides. Les prédictions d'humidités disponibles des soles ont été calculées pour les différentes catégories d'IPS. L'humidité disponible des soles est au plus bas pour les mois de mars et d'avril. De plus, les demandes en irrigation pour la production de légume et de canne à sucre ont été déterminées pour les catégories d'IPS Modérément Sec et Sévèrement Sec de sécheresse dans les mois plus secs de l'année, et ce dans les trois sites étudiés.

SWAT a été utilisé pour modeler l'hydrologie du basin versant de Rio Nuevo dans la région de St-Mary en Jamaïque. SWAT a été calibré et validé en utilisant des mesures de débit couvrant la période 2002 à 2007. Les performances du modèle sont considérées satisfaisantes, ayant obtenu une Efficacité Nash-Sutcliffe de 0.78 pour la calibration et de 0.52 pour la validation. Les résultats obtenus ont été utilisés afin de déterminer les capacités du débit à répondre aux demandes d'irrigation d'un bassin

inférieur du bassin versant. Il a été déterminé que pour la sécheresse de 2000, le débit était insuffisant et ne pouvait répondre aux demandes d'irrigation de janvier à mars.

## ACKNOWLEDGEMENTS

Firstly, I would like to thank God for providing the means for me to pursue this research, as well as providing me with people who have given me extraordinary emotional support. Next, I would like to thank both of my parents, for their undying faith and pride in me. Their high standards of excellence have molded me into the researcher I am today.

The success of this work is also a reflection of the dedication to excellence of the people working with me. Dr. Chandra Madramootoo has been fundamental to the success of this work, both through his financial support, as well as through his vision and direction for this work. Mr. Adrian Trotman, acting in the capacity as my co-supervisor for several aspects of this research, is also deeply appreciated for his deep insight and commitment to this work.

The help of Andreas Haiduk from the Jamaica Water Resources Authority has been absolutely critical, and I can firmly say that this research would not have seen the level of success it has, had it not been for his assistance in providing both insight and streamflow data.

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I would like to thank all my office mates and colleagues for their continued support during this time. Apurva Gollamudi and Marie-Claire St. Jacques, thank you so much for your insight and assistance during this research. Colline Gombault, not only did you provide me with help in learning SWAT, you were the ear I turned to when I was frustrated. Thank you for being a quiet, yet powerful, support for me.

To Dr. Marcia Knutt, and to my ‘adopted’ Aunt Yvonne Williams, I would like to extend my deepest gratitude. Both of you have played pivotal roles in this work with your powerful insight and unwavering emotional support, and for this I am infinitely in your debt.

To all others: my friends, my family, teachers and colleagues, it was a fantastic journey, and I truly believe that together we have performed an extraordinary study that will have significant impacts on water resources planning in Jamaica.

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# NOMENCLATURE

$\alpha$: Confidence level in hypothesis tests

$\alpha_{pet}$: A coefficient in the Preistley Taylor method

Δ : The slope of the saturation vapor pressure-temperature curve, de/dT (kpa $˚C^{-1}$) in the Preistley Taylor method

Δt :The length of the time step in SWAT model

$\infty$ : Infinity

a: A parameter of the Gringorten plotting formula

ADI: Aggregated Drought Index

AGNPS: Agricultural Non-point Source Pollution Model

ALPHA_BF: Baseflow Alpha Factor

ANSWERS: Areal Non-point Source Watershed Environment Response Simulation

AVHRR: Advanced Very High Resolution Radiometry

BANA: Bananas landuse in SWAT

BBDB: Bamboo and Broadleaf landuse in SWAT

BBFD: Bamboo and Fields landuse in SWAT

CABG: Cabbages landuse in SWAT

CARIWIN: Caribbean Water Initiative

CDEMA: Caribbean Disaster Emergency Management Agency

CDF: Cumulative Distribution Function

CDPMN: Caribbean Drought and Precipitation Monitoring Network

CIDA: Canadian International Development Agency

CIMH: Caribbean Institute of Meteorology and Hydrology

CN: Curve Number

CPC: Climate Prediction Center

D: Maximum deviation (applied in the Kolgomorov-Smirnoff test)

$D_a$: Depth of water supplied per irrigation application

DBFD: Disturbed Broadleaf and Fields landuse

DEM: Digital Elevation Model

DSBL: Disturbed Broadleaf landuse

$E_a$: The amount of evapotranspiration on day i in SWAT model

ENSO: El Niño/ Southern Oscillation

$ET_c$: Monthly actual crop evapotranspiration

$ET_p$: Monthly potential evapotranspiration

$E_o$ :The potential evapotranspiration per day

ESCO: Soil Evaporation Compensation Factor

ET: Evapotranspiration (predicted by SWAT)

$f$ : A correction factor which depends on the depth of the irrigation water supplied per application

F :The probability of non-exceedance in a frequency analysis

$F_p$ : The predicted value of the CDF

F’: Probability of exceedance

$F'_l$: Lower limit of probability of exceedance on confidence interval

$F'_u$: Upper limit of probability of exceedance on confidence interval

$FC_{ly}$ :The water content of the layer at field capacity in SWAT model

$FC_{ly}$ :The water content of the soil layer at field capacity in SWAT model

FIDS: Fields landuse in SWAT

G : The heat flux density to the ground in the Preistley Taylor method

GDP: Gross Domestic Product

Ge: Monthly Groundwater contribution from water table

GEV: Generalized Extreme Value

GIS: Geographic Information Systems

GUI: Graphical User Interface

GW_DELAY: Groundwater delay time

GW_REVAP: Groundwater ‘revap’ coefficient

GWQMN: Threshold depth of shallow water in the aquifer required for return flow to occur

HEC-HMS: Hydrologic Engineering Centre Hydrologic Modelling System

$H_{net:}$ The net radiation in the Preistley Taylor method

$H_{0:}$ The null hypothesis in the Chi Square distribution

HRU: Hydrologic Response Unit

HTPR: Hot peppers landuse in SWAT

$IR_n$: Net Irrigation Requirement

IWRM: Integrated Water Resources Management

j: The value immediately before and after an event value at time t (for deseasonalization process)

KS: Kolgomorov-Smirnoff

$K_{sat}$ :The saturated hydraulic conductivity for the layer in SWAT model

LATQ : Lateral shallow sub-surface flow to the reach (predicted by SWAT)

LR: Monthly Leaching Requirement

$L_s$ : Moisture loss from the surface layer

$L_u$: Moisture loss from the underlying soil

m: Rank of the data for frequency analysis

mm: Millimeter

n: number of years of data

NCDC: National Climatic Data Center

NDVI: Normalized Difference Vegetation Index

NOAA: National Oceanic and Atmospheric Administration

NRCS: Natural Resource Conservation Service

NSE: Nash Sutcliffe Efficiency coefficient
OAT: One-at-a-time
ODPEM: Office of Disaster Preparedness and Emergency Management
P: Monthly precipitation
Pe: Monthly Effective Rainfall
$P_m$ : The theoretical probability of an outcome being in class *m* under the Kolmogorov-Smirnoff test
$P_X$: The specified theoretical cumulative distribution function under the null hypothesis under the Kolmogorov-Smirnoff test
PBIAS: Percent Bias coefficient
PCP: Precipitation (as input into SWAT)
PDF: Probability Distribution Function
PDSI: Palmer's Drought Severity Index
PERC: Deep water percolation
PN: Percent of Normal
$Q_{gw}$: The amount of return flow on day i in SWAT model
$Q_{surf}$ : The amount of surface runoff on day i in SWAT model
$R^2$: Regression coefficient
$R_{day}$ : The amount of precipitation on day i in SWAT model
RCHDP: Deep Aquifer Percolation Fraction
REVAPMN: Threshold depth the shallow aquifer required for deep percolation to occur
RSR: Ratio of the root mean square error to the standard deviation of measure data (RSR)
$S_N(x)$: The sample cumulative distribution function based on N observations under the Kolmogorov-Smirnoff test
$S'_s$: Available moisture in the surface layer at the start of the month
$S'_u$: Available moisture stored in the underlying soil at the start of the month
SAS: Statistical Analysis System
$SAT_{ly}$ :The amount of water in the layer when completely saturated in SWAT model
SCS: Soil Conservation Service
SPI: Standardized Precipitation Index
SURQ is the surface runoff (predicted by SWAT)
SWa: Plant Available Water stored in the soil at the end of each month
$SW_0$ : Initial soil moisture content on day i in SWAT model
$SW_{ly}$ : The water content of the soil layer on a given day in SWAT model
$SW_{ly,excess}$ :The drainable volume of water in the soil layer on a given day in SWAT model
$SW_t$: Final soil moisture content predicted in SWAT model
SWAT: Soil and Water Assessment Tool
T: Return period
TOMA: Tomatoes landuse in SWAT
TS : Sixteen-day mean in a time series

$TS_{sm}$: Seasonal value of the time series

$TS_{ds}$: Deasonalized time series value

$TT_{perc}$ :The travel time for percolation in SWAT model

U.S.: United States

USD: United States Dollar

USDA: United States Department of Agriculture

USLE: Universal Soil Loss Equation

W: The change in soil moisture depth

$w_{ac}$: Available water capacity of the soil

$w_{seep}$: The amount of water entering the vadose zone of the soil profile on day I in SWAT model

$W_{perc,ly}$ :The amount of water percolating to the underlying soil layer on a given day in SWAT model

WA: Wavelet Analysis

WNW-ESE: West North West- East South East

$X_m$: The number of outcomes in class m under the Kolmogorov-Smirnoff test

# CONTRIBUTIONS OF AUTHORS

The principal author of this thesis and all manuscripts therein is Johanna Richards. However, Dr. Madramootoo, acting in the capacity of my primary supervisor, is the secondary author for all three manuscripts. Mr. Adrian Trotman was my co-supervisor for the research involving the development of drought indices for Jamaica. As a result, he is listed as a co-author on Chapter 4 of this manuscript.

# CHAPTER 1: Introduction

Jamaica is an island situated in the north-western Caribbean Sea, and is centered along latitude 18˚15' N, and longitude 77˚ 20' W. It is covered by mountainous terrain, with its topography consisting of high interior lands oriented along a WNW-ESE alignment through the centre of the island, surrounded by coastal plains (UWAJ, 1990). Daily temperatures in the coastal lowlands average 26.2 ˚C, with a range from 22˚ C to 30.3˚ C (Meteorological Service of Jamaica, 2009). For every 300 meter increase in altitude above sea level, there is a 2˚ C drop in temperature.

Rainfall is the most variable of all the climatic parameters in Jamaica. The one hundred year mean annual rainfall for the island (1890 – 1990) is 1895 mm. However, some mountainous areas receive more than 5080 mm annually, while coastal areas to the south-east of the island receive less than 889 mm annually (Meteorological Service of Jamaica, 2009). The rainfall pattern throughout most of the island is bi-modal, meaning that there are two wet periods throughout the year. These seasons occur in September to November, and May to June (Meteorological Service of Jamaica, 2009). December through to March is typically the driest period of the year.

The Jamaican agricultural sector employs approximately 20% of the labour force (FAO, 2003; PIOJ, 2008). The main crops are sugar, bananas, citrus, coffee, cocoa and coconuts (MOA, 2007). However, the agricultural sector has been threatened recently by globalization, as well as changing climatic systems (Ricketts, 2005).

Agriculture in the West Indies is heavily dependent on seasonal rainfall, and this is especially true of Jamaica where approximately 10% its cultivated lands are irrigated. The main irrigated crop is sugar cane, which accounts for 70 to 80% of the irrigated land. The majority of irrigation systems are located in areas characterized by dry climatic conditions (effective rainfall normally below 1000mm/year) (Ministry of Water and Housing, 2004). As a result, the planting/harvesting cycles of the majority of small farmers revolve around the wet and dry seasons. Estimates of agricultural production in Jamaica indicate that 95% of this production is rain-fed (Chen et al., 2005).

Of the extreme climatic events, drought is the one that affects the largest number of people and largest territory worldwide (Calcagno et al., 2007). It also causes the greatest economic damage, resulting in six to eight billion USD in global damages annually (Wilhite, 2000). However, if a timely and reliable drought monitoring system is in place, then an effective mitigation of drought impacts is possible (Cancelliere et al., 2007). In the 2000/2001 drought experienced in Jamaica, there were crop losses amounting up to six million USD (Trotman et al., 2009). Drought is a slowly developing process, the results of which might not be evident until months after its onset

(Keyantash and Dracup, 2002). As a result, the ability to monitor and anticipate the onset of drought is important for alleviating the negative impacts of this phenomenon.

McGill University, in association with the Caribbean Institute of Meteorology and Hydrology, has developed the Caribbean Water Initiative (CARIWIN), which aims to promote integrated water resources management practices in the Caribbean region. The development of drought indices has been identified by water resources managers and stakeholders in the CARIWIN countries as being an important step in the advancement of an integrated water resources management program, and has been identified as a high priority for research in respect to the CARIWIN project (Trotman et al., 2008). Through CARIWIN, the Caribbean Drought and Precipitation Monitoring Network (CDPMN) was proposed as a framework in which these indices could be developed.

Drought indices can only be effective if the stakeholders who will be using them understand what the indices actually represent within a physical context. This research aimed to correlate both the Standardized Precipitation Index, as well as the Normalized Difference Vegetative Index to monthly available soil moisture.

In order to manage and assess water stressed conditions in Jamaica, this research has also engaged in the development of irrigation requirements for both sugarcane and vegetables, for three sites in Westmoreland, Clarendon and St. Thomas. In addition, monthly and seasonal rainfall frequency analyses were also performed for the three study areas. Lastly, the Soil and Water Assessment Tool was used to determine its ability for simulating streamflow in the Rio Nuevo sub-basin, in order to evaluate the potential of the model for assessing irrigation management scenarios.

## 1.1 Objectives

The main objectives of this study were to:

i) Determine monthly irrigation demands for vegetables and sugarcane, for the three study sites, using monthly available soil moisture conditions.
ii) Use the Standardized Precipitation Index (SPI), as well as the Normalized Difference Vegetation Index (NDVI) for three study sites, and determine the relationship between the index values and available soil moisture on a monthly basis.
iii) Calculate monthly irrigation demands for the three study sites using the predicted available soil moisture values determined through the relationship between the drought indices and soil moisture.
iv) Model the hydrology of the Rio Nuevo sub-basin, located in St. Mary, Jamaica, with the Soil and Water Assessment Tool (SWAT), for use in performing

irrigation management scenarios for determining agricultural water savings potential, leading to a more preparation based response to water scarcity management.

## 1.2 Scope

Both the SPI and NDVI were used for the study sites. Each study area is unique in terms of soil type and precipitation characteristics. However, despite these unique physical properties, the results for these sites can be extended to surrounding areas, at least until further studies are carried out for other areas. In addition, SWAT was used to model the Rio Nuevo watershed. The model was built specifically for the Rio Nuevo watershed and so the simulation results are limited to the watershed. As such, care should be applied when applying the results to other parts of the island.

## 1.3 Thesis outline

This thesis is presented as a series of chapters, each of which contributes collectively and comprehensively to the objectives stated above. A literature review of watershed hydrology, drought behaviour and monitoring, hydrological models and hydrology modelling in SWAT, as well as rainfall frequency analyses is presented in Chapter 2. Following this chapter are a series of chapters which outline sequentially the methodology and results of the various facets of the research. Chapter 3 describes the determination of irrigation demands for both sugarcane and vegetables. In addition, it describes the results of a seasonal rainfall frequency analysis of two of the growing seasons in Jamaica. Chapter 4 describes the development of the SPI and NDVI, as well as their applicability for representing soil moisture. Chapter 5 describes the investigation into the feasibility of SWAT for simulating the streamflow of the Rio Nuevo basin, while also describing the use of SWAT in irrigation planning. Lastly, Chapters 6 and 7 summarize the findings and results of the research, while providing direction for future research initiatives.

# CHAPTER 2: Literature Review

## 2.0 Definition and forms of drought

Drought is a naturally recurring feature of climate which occurs in all climatic zones. The characteristics of drought vary significantly from region to region, and it is different from aridity, which is a permanent feature of climate and is restricted to low rainfall regions (Bordi and Sutera, 2007). The term *drought* refers to a constant reduction of water availability with respect to normal (mean) values. This reduction affects a wide region, and spans a significant period of time. There is no universal and all-compassing definition of drought, as it cannot be viewed as a purely physical phenomenon, but must also be considered in relation to its impacts on society (Bordi and Sutera, 2007). Many different definitions of drought therefore exist, but the definitions which used for the purpose of this research are those of the American Meteorological Society (1997), and are based on the definitions by the World Meteorological Organization, both of which classify drought into four categories: meteorological, agricultural, hydrological and socio-economic. Each type of drought has specific characteristics and affects different aspects of society.

Meteorological, agricultural and hydrological droughts are traditionally defined by the deficient hydrologic component (Keyantash and Dracup, 2004). Meteorological drought is characterized by a shortage of precipitation, and represents a departure of precipitation values from normal conditions over a period of time (Bordi and Sutera, 2007). The variability in precipitation is *likely* caused by sunlight energy fluctuations, or earth processes such as geophysical and oceanographic interactions (Rossi et al., 2007). Agricultural drought is characterized by a shortage of available soil moisture content, and is defined as a deficiency in the soil moisture content needed to replenish evapo-transpirative losses from crops (American Meteorological Society, 1997). Hence, agricultural drought reflects the relationship between meteorological drought and its effects on crops. It is affected by the differences between real and potential evapotranspiration, the moisture deficit of the soil, and the lack of rainfall etc. (Byun and Wilhite, 1999). Hydrological drought is characterized by a shortage in surface and sub-surface water supplies due to precipitation shortages over an extended period of time (Bordi and Sutera, 2007). This affects segments of the water cycle such as stream flow and reservoir storage (Wilhite, 2000). Lastly, socio-economic drought occurs when the water demand exceeds supply, thus causing the shortage of water to affect people, resulting in social, economic and environmental impacts (Bordi and Sutera, 2007).

## 2.1 Drought in Jamaica

### 2.1.1 An overview of Jamaica's water resources

All of Jamaica's freshwater is obtained from precipitation in the form of rainfall. Of the total precipitation that Jamaica receives (21,211 MCM/yr), 57% of that is lost through evapotranspiration, while 26% goes to surface water runoff. Lastly, 17% of the precipitation becomes groundwater recharge (WRA, 1990). Agriculture is by far the largest user of water within the Island, accounting for 80% of the national water demand. Non-agricultural use accounts for the remaining 20% of the demand, and includes domestic, touristic and industrial use. The total water demand in the Island is 1,437 MCM/yr (WRA, 2010). This is expected to rise to 1,684 MCM/yr by 2015.

Groundwater constitutes the most important source of Jamaica's freshwater resources, constituting 84% of the Island's freshwater. The remaining 16% comes from the island's rivers (WRA, 2010). Limestone (karstic) aquifers occupy almost 50% of the Island's area. Due to the high infiltration capacity and well developed sub-surface system of limestone aquifers, the outcrops are characterized by a noticeable lack of surface streams (WRA, 1990). These karstic aquifers result in complex interactions between surface and groundwater flow. The remaining hydro-stratigraphic units in the island are aquiclude, which severely restrict the surface-groundwater flow interactions, as these units do not allow for the significant movement or storage of groundwater (WRA, 2010).

### 2.1.2 Occurrence of drought in Jamaica

Drought in the West Indies is often related to disruptions in the seasonal rainfall cycle. The El Niño/Southern Oscillation (ENSO) is the primary phenomenon associated with these seasonal disruptions (Chen et al., 2005). Decadal fluctuations in rainfall amounts can also cause drought (Taylor et al., 2002). When an El Niño event occurs, the climate of the West Indies is characterized by drier than normal conditions during the later months of the rainfall season. Many Island-wide meteorological droughts occurring in 1965, 1969, 1972, 1976, 1982-83, 1991, and 1997 have been caused by El Niño events (Chen et al., 2005). However, in 1976 and 1991, the island received 72% and 73%, respectively of normal total annual rainfall with respect to a 30-year mean, resulting in the worst drought conditions during that period (Chen et al., 2005).

Interestingly enough, La Niña events in the cold equatorial Pacific waters, can induce drought conditions in the early rainfall season of the following year. This scenario has been deemed the cause of the island wide meteorological droughts that occurred in

Jamaica in 1971, 1974, 1975, 1985, 1989 and 2000 (Chen et al., 2005). The territories of the island that are the most prone to drought are located between the parishes of St. Elizabeth to St. Thomas inclusive.

## 2.2 Theory of drought management

As drought is considered to be a natural event of unpredictable yet recognizable occurrence, it is considered a hazard. However, as it also corresponds to the disruption of water supply to human and ecological systems, it is considered a disaster (Pereira et al., 2002). Due to the long period of time over which drought spans however, more effective mitigation of the adverse effects can take place than say, for a flood or earthquake, provided that effective and timely monitoring of an impending drought takes place (Cancelliere et al., 2007).

There are several major challenges in dealing with drought. The first challenge is that drought is a “creeping phenomenon”, as it is difficult to identify its beginning and end (Glantz, 1987). The reason for this is that neither the onset, nor the end, of drought has a sharp distinction from non-drought periods (Glantz, 1987). Another challenge, particularly in developing countries when dealing with drought, is that no long term development policies are put into place for drought management (Glantz, 1987). Policy makers and government officials tend to view drought as a transient and peculiar event. It is typically considered to be an event which will not recur for a long time, especially because the long term effects of the drought are usually downplayed by the return of the rain. Lastly, the impacts of drought on human activities can be very subtle and far-reaching (Glantz, 1987). There are the obvious effects, such as withering of crops. However, there are also much more subtle effects, such as increased rural-to-urban migration rates and food price increases.

It is equally difficult to determine drought severity. The severity of the drought will determine the impacts on society, environment and the economy, which are difficult to identify and to quantify. The duration, intensity and geographical extent of a drought episode, as well as human and ecological demands, all play a part in defining the severity of a drought (Wilhite and Glantz, 1987). Consequently, even though drought may not be solely responsible for many of the unfortunate societal and economic impacts which occur during drought periods, its combination with other factors affecting a region or country at that specific time can be devastating, severely hindering the development process (Glantz, 1987).

Table 2.1 shows some of the economic, environmental and social impacts which drought can have. The effects can be far reaching and catastrophic. Several studies have been done on the management of drought in various regions, and these studies have highlighted the fact that much work needs to be done on improving the current strategies for mitigating drought impacts. For example, recent drought events in the Mediterranean region have drawn attention to the insufficiencies of the current strategies for alleviating the impacts of drought on the different socio-economic sectors related to water use (Rossi et al., 2007). The lack of effective drought monitoring and forecasting systems has also been identified as one of the main factors preventing the implementation of effective water policies (Rossi et al., 2007). The process of properly selecting and implementing mitigation measures is hindered by the complexity associated with defining simple and objective criteria for drought risk assessment (Rossi et al., 2007).

**Table 2.1: Drought impacts**

| Economic Impacts |
|---|
| 1) Damage to agricultural production (crop reduction, damage in cultivations, plant diseases)<br>2) Damage to fishing (damage to river habitat etc.)<br>3) Damage to tourism sector due to reduced water supply<br>4) Loss to industries connected with the agricultural sector (food industries, fertilizer industries etc.) |
| Environmental Impacts |
| 1) Increase of salt-water intrusion (streams, groundwater)<br>2) Damages to river life (flora and fauna) |
| Social Impacts |
| 1) Health risks associated with increases in pollution concentrations and discontinuous water systems<br>2) Inconveniences due to water system rationing |

Drought creates new land and soil quality problems, in addition to exposing and exacerbating old ones (Glantz, 1987). In order to prevent and mitigate the impacts of future drought occurrences, effective water resources planning must take place. The first step in this planning is an objective evaluation of the drought condition (Bordi and Sutera, 2007). For this purpose, several indices have been developed over the years which evaluate the relationship between the water supply deficit and the time duration of the precipitation shortage (Keyantush and Dracup, 2002).

The use of drought indices in many countries is increasing. These countries include the United States, Canada, Australia and many European countries (Wilhite et al., 2000). Several different indices have been developed, each one taking into account a different form of drought. Among the most popular of these indices are the Percent of

Normal, the Standard Precipitation Index (SPI), and the Palmer's Drought Severity Index (PDSI) (Bordi and Sutera, 2007; Keyantash and Dracup, 2002). The Aggregated Drought Index (ADI) has been very recently published by Keyantush and Dracup (2004), and to this point has not been widely used. In general, these indices are based on precipitation amounts, utilizing the standard deviation of these indices from a historical norm (Bordi and Sutera, 2007).

There are some indices, including the Palmer's Drought Severity Index and the Aggregated Drought Index, which take into account other climatological variables such as soil moisture, streamflow, and evapotranspiration. However, it is often extremely beneficial to be able to compare conditions of different areas, and so the standardization of an index is an important characteristic (Bordi and Sutera, 2007). In this respect, the Standard Precipitation Index and the Aggregated Drought Index have an advantage over the other indices. More information on each of these indices is provided in the following sections.

It is worth mentioning, that Rossi et al. (2007), point out that the impacts of a drought on different sectors depend mainly on the pre-existing vulnerability of that sector. They mention that for a water supply system, the risk of a water shortage problem depends not only on the severity of the drought event, but also on the strength of the preventative planning, administration and management associated with the system.

The use of drought indices is one of many steps in the drought mitigation process. Other steps include increases in water supply (inter-basin transfer, weather modification etc.), reduction in water demands and drought impact minimization (drought resistant crops etc.) (Rossi et al., 2007).

## 2.3 Drought mitigation strategies in Jamaica

There are drought mitigation strategies which exist at the national level. In the event of prolonged drought, the Rapid Response Unit under the Jamaican Ministry of Water and Housing is responsible for installing water tanks in households and on farms for a reduced cost (Chen et al., 2005). This is done in an effort to reduce the impacts of drought on humans, crops and livestock. The Government of Jamaica, through the Office of Disaster Preparedness and Emergency Management (ODPEM) has prepared a drought plan which utilizes a multiple-agencies approach to drought management, and addresses domestic, agricultural and industrial water needs throughout the island. It addresses the different facets of drought management, including preparedness, mitigation, emergency response, rehabilitation and development (Chen et al., 2005). During a period of meteorological drought as determined by the Meteorological Service of Jamaica, it calls for the activation of a response team. The Meteorological Service of

Jamaica issues warnings and alerts to the ODPEM and other agencies, including the Ministry of Agriculture, as well as the Rural Agricultural Development Agencies. The use of drought indices, as mentioned in the previous section, would be a valuable tool for use in the drought plan currently in place.

## 2.4 Caribbean Drought and Precipitation Monitoring Network (CDPMN)

The Caribbean Drought and Precipitation Monitoring Network (CDPMN) was launched in January 2009 under the Caribbean Water Initiative (CARIWIN) program. This program is a joint project between the Caribbean Institute of Meteorology and Hydrology (CIMH), and McGill University, and is funded by the Canadian International Development Agency (CIDA). The purpose of CARIWIN is to increase the capacity of Caribbean countries to engage in Integrated Water Resources Management (IWRM) practices (Trotman et al., 2009). CARIWIN was launched in January 2007 and is expected to be a six year project. It includes a partnership with Guyana, Grenada and Jamaica.

There are several expected outcomes and benefits of the CDPMN. Overall, the network is expected to aid in the planning and adaptation to drought and heavy precipitation, thus improving the management of water resources (Trotman et al., 2009). There are four main functions of the CDPMN, obtained from Trotman et al. (2009). These functions are to:

1) Post warnings on the CIMH website and disseminate these warnings to relevant agencies, governments and media in partner countries
2) Monitor the status of rainfall through the use of climatic and hydrologic indicators, as well as any other relevant indicators
3) Couple seasonal forecasts with drought monitoring in order to make projections with lead times up to three months
4) Create a network of researchers working with stakeholders, including all levels of government from local to national, which will collectively enable the development of adaptation and resource response strategies to drought and excessive rainfall.

## 2.5 Overview of drought indices

### 2.5.1 Percent of normal

The Percent of Normal (PN) requires precipitation as its only input, usually over a minimum 30 year historical period. It is calculated by dividing actual precipitation by normal precipitation, in general considered to be a thirty year mean, and multiplying this by 100% (Bordi and Sutera, 2007). Normal precipitation for a particular area is considered to be 100%. The Percent of Normal is currently the primary meteorological drought index being used in Jamaica (Chen et al., 2005; Meteorological Service of Jamaica, 2009). The Percent Normal can be computed over a variety of time scales, which can range from a single month to a group of months. The time scale will vary depending on whether or not the water planners are interested in looking at a season, or an annual or water year, which will in turn, depend on the purpose of the index (Bordi and Sutera, 2007).

A disadvantage of the Percent of Normal is that it is difficult to compare climatic conditions of different areas. This is due to the fact that precipitation on monthly or seasonal scales does not have a normal distribution, and so, the mean is not the same as the median precipitation (Bordi and Sutera, 2007). The median precipitation is the value exceeded by 50% of the precipitation occurrences in a long-term climatic record. This shortcoming has been overcome by both the SPI and the ADI.

### 2.5.2 Standardized Precipitation Index (SPI)

The Standardized Precipitation Index (SPI) was developed by McKee et al. (1993) and since then has been applied extensively in many parts of the world including the United States (Hayes et al., 1999), Australia (Barros and Bowden, 2008), Europe (Cancelliere et al., 2007) and Africa (Ntale and Gan, 2003). It is the most internationally used drought indicator (Andreau et al., 2007). The index is computationally simple and is time-flexible, meaning that it can be developed over different time scales (Bonaccorso et al., 2003; Cancelliere et al., 2007; Guttman, 1998; Mendicino et al., 2008). This time flexibility gives the indices versatility, in that indices developed over short term time scales are applicable for monitoring short term meteorological drought. At the same time however, indices developed over long term time scales are applicable for the purposes of water resources management as well as the monitoring of long term (agricultural, hydrological and socio-economic) drought (Cacciamani et al., 2007; Guttman, 1998). These time scales in general range from three months to twenty-four months (Moreira et al., 2008).

The SPI is spatially and temporally normalized, and is therefore applicable to both wet and dry climatic conditions. In addition, it can be applied regardless of location (Cancelliere et al., 2007). This allows it to be used on a regional basis, and so climatic conditions/developments can be monitored in the Caribbean using this standardized system of monitoring. Incidentally, this is what the Caribbean Drought and Precipitation Monitoring Network (CDPMN) is attempting to do. Keyantash and Dracup (2002) compared the performance of several drought indices, including the SPI, the Palmer Drought Severity Index (PDSI), the Percent Normal index, and the Surface Water Supply Index. It was determined, based on the evaluation of several parameters such as robustness, tractability, transparency, sophistication, extendability and dimensionality, that overall, the SPI was the most suitable index for monitoring both long and short term drought events.

There are pre-defined categories for the SPI as defined by the U.S. National Oceanic and Atmospheric Administration (NOAA) National Climatic Data Center (NCDC). The categories that represent water scarcity have been defined by NOAA NCDC as Near Normal, Abnormally Dry, Moderately Dry, Severely Dry, Extremely Dry and Exceptionally Dry (NCDC, 2010). Each of these categories is defined by a range in SPI values. For example, the Near Normal category is defined by a range in SPI values of -0.5 to 0.5, while the Abnormally Dry category is defined by a range of -0.79 to -0.51 etc. The more negative the value, the more severe the form of drought.

In order to develop the SPIs, monthly precipitation data over a period of 30 years is fitted to a frequency probability distribution, usually a Gamma distribution. This distribution is then normalized (transformed through an equal probability distribution to a normal distribution) in order to allow the SPIs to be applicable regardless of location and climatic conditions (Bordi and Sutera, 2007). Positive and negative SPI values indicate greater than or less than median precipitation respectively (Bordi and Sutera, 2001). One main disadvantage of the SPI is that it is not always easy to find a probability distribution that fits the data. In addition, access to sufficiently long and reliable monthly precipitation data (at least 30 years) might not be available (Cacciamani et al., 2007).

### 2.5.3 Palmer's Drought Severity Index (PDSI)

The Palmer's Drought Severity Index (PDSI) was introduced by Palmer (1965) and was widely used before the introduction of the SPI for drought monitoring purposes. This index is based on the water balance, using a supply and demand concept over a two-layer soil model. The PDSI is based on the deficit between actual precipitation, and the precipitation required to achieve a normal water balance. Various coefficients, which define local hydrological norms related to temperature and precipitation, are required for the development of the PDSI. The calculation of these coefficients depends heavily on the available water capacity of the underlying soil layer in the two–layer soil system (Bordi and Sutera, 2007).

### 2.5.4 Aggregated Drought Index (ADI)

The Aggregated Drought Index (ADI), developed by Keyantash and Dracup (2004), takes the assessment of drought a step further than the SPI, PDSI and PN, in order to provide a comprehensive analysis of physical drought. It takes all three physical forms of drought into consideration through the analysis of variables that are indicators of each type. It is a multivariate drought index that takes into account the overall water balance across the three physical regimes of drought (Keyantash and Dracup, 2004). The six parameters which are taken into account in the development of the ADI are precipitation, evapotranspiration, streamflow, reservoir storage, soil moisture content and snow water content (Keyantash and Dracup, 2004). One parameter which is not included in the development of the ADI is groundwater storage. However, according to the authors, groundwater was not considered because of the difficulty of assessing flow throughout watershed/climatic boundaries. Another reason is the large timescale of groundwater flow, which is typically over a timescale of weeks to years, extending beyond the ADI time step of one month (Keyantash and Dracup, 2004).

Keyantash and Dracup (2004), used soil moisture data obtained from the U.S. Climate Prediction Center (CPC), on a climatic division basis. The CPC used the one-layer soil moisture developed by Huang et al. (1996), which is based on the water budget of the soil. The inputs of the model are monthly mean temperature and monthly mean precipitation, and the model obtains results for climatic zones.

### 2.5.5 Remote sensing- Normalized Difference Vegetation Index (NDVI)

The NDVI is an index that is used in order to measure and monitor plant growth and vegetation cover, and is derived from remote sensing measurements (USGS, 2010). It is calculated from the red and near-infrared reflectance from vegetation, which is measured by satellite. It is calculated by the ratio (near-infrared - red)/(near-infrared + red) (Samson, 1993). High correlations have been found between the NDVI and vegetation parameters such as green-leaf biomass, as well as green leaf area (Van De Griend and Owe, 1993). Green leaves have higher NDVI values than yellow or dry leaves. As such, the NDVI values will increase with increasing vegetation cover and biomass, with bare soils having the lowest values (Van De Griend and Owe, 1993). The NDVI ranges from -1 to 1, with 0 representing no vegetation. Negative values represent non-vegetative surfaces, while values approaching 1 represent very dense vegetation (Anyamba et al., 2005).

The NDVI has also been found to be well-correlated to monthly mean soil moisture values in previous studies (Farrar et al., 1994). However, the NDVI was found to represent soil moisture better in dry years as opposed to wet years, due to a high soil moisture availability (Narasimhan et al., 2005). Narasimhan et al. (2005) also found that the NDVI provides a good representation of soil moisture, and can be used as a good agricultural drought indicator. Narasimhan et al. (2005) mentioned that the NDVI did not correlate well to soil moisture for brush species in rangeland and trees in forest land, however it responded well to changes in soil moisture for agricultural and pasture lands.

### 2.5.6 Selection of the SPI for development in Jamaica

It has been determined that the Standardized Precipitation Index (SPI) is the most suitable meteorological index that can be developed for the island of Jamaica as a whole. A disadvantage of the SPI is that it does not take into account the effects of soil, land use characteristics, aquifers etc. (Mendicino et al., 2008; Narasimhan et al., 2005). The Palmer's Drought Severity Index (Palmer, 1965) is traditionally one of the most popular indices used in the United States. This index attempts to deliver spatially variable drought indices by taking into account the overall water balance. However, this index has limitations, including, but not limited to, the fact that (i) it has complex, empirical derivations, (ii) the underlying computations are based on the climates of the mid-western United States and (iii) it assumes that parameters such as land use are uniform over the entire climatic zone (Guttman, 1998; Keyantash and Dracup, 2002; Narasimhan et al., 2005).

Despite the fact that all three indices have their limitations, the SPI will be the most feasible for use in the Jamaican context due to the fact that (i) only precipitation data is required (ii) it is standardized over different climatic and temporal scales and (iii) a significant amount of literature already exists on its use and applications, especially in the context of developing countries.

### 2.5.7 Available soil moisture

Field capacity is the moisture content of the soil above which water will drain from the soil by gravity. The wilting point of the soil is the moisture content, below which, the plant cannot further extract water (Bedient and Huber, 2002). The difference in moisture content between the field capacity and the wilting point is the available soil moisture. Excessive water (water which causes the moisture content in the soil to exceed field capacity), will cause waterlogging, resulting in the death of the plant roots due to lack of oxygen (Ley et al., 1994). It is essential that the soil moisture content be kept, as much as possible, between field capacity and wilting point.

The characteristics of the soil will affect the ability of the soil to hold water. Both soil texture and soil structure affect the ability of the soil to store water (Hughes and Evans, 1999). Clay soils have a higher capacity for retaining water than sandy soils, and well structured soils with a high organic capacity will also have a higher water retaining capacity (Sammis and Mexal, 1999). Schwab (1993) provides some generic field capacity and wilting point values for various soils on a volumetric basis. The typical ranges of these values are shown in Table 2.2 below.

**Table 2.2: Generic soil moisture properties for various soils**

| Soil texture | Field capacity (by % volume) | Permanent wilting point (by % volume) | Plant available water (by % volume) |
|---|---|---|---|
| Sandy | 10-20 | 3-10 | 6-10 |
| Sandy loam | 15-27 | 6-12 | 9-15 |
| Loam | 25-36 | 11-17 | 14-20 |
| Clay loam | 31-42 | 15-20 | 16-22 |
| Silty clay | 35-46 | 17-22 | 18-23 |
| Clay | 39-49 | 19-24 | 20-25 |

## 2.6 Overview of hydrological models

Reliable knowledge of the hydrologic cycle is essential for effective water resources management (Jain and Sudheer, 2008). However, certain components of the cycle such as soil moisture content and evapotranspiration are extremely difficult, and in most cases impossible (especially in developing countries), to acquire over long historical periods and large territories. The several hydrological models which are available for hydrological modeling can be divided into two main categories: distributed and lumped. Distributed hydrologic models have the capability of incorporating a variety of spatially varying land and precipitation characteristics (Carpenter and Georgakakos, 2006). Lumped hydrologic models, on the other hand, are not spatially explicit, and represent the collective effects of land use changes in a watershed (Ward and Robinson, 2000). Due to the fact that this research relies heavily on the ability to model the watershed over a spatially variable scale, the overall focus of discussion in the following sections will be on distributed models.

### 2.6.1 V*flo*

Vflo™ is a high resolution, fully-distributed hydrologic model which can be used for the management of water on a catchment to river basin scale. *Vflo™* can model the flow rate and depth of water bodies at any location in the watershed. The model can be used in real-time operation, and as a tool for continuous flood forecasting, drainage design and water management (Vieux, 2009). It has been applied to projects such as the investigation of the impacts of landuse changes, flood event reconstruction, operational flood alerts and the research and analysis of hydrologic phenomena (Vieux, 2009).

While Vflo™ simulates hydrologic processes over a high spatial resolution, it also requires high resolution inputs in order to gain these results. Unlike other hydrologic models, Vflo™ was actually designed to “take advantage” of high resolution Geographic Information Systems (GIS) datasets as well as the spatial variability of radar rainfall (Vieux, 2009). Even though the modeling capabilities of Vflo™ are extensive and powerful, it was not deemed to be the right software to be used in Jamaica, where access to radar and high resolution GIS data over any long periods of time is very difficult, if not impossible, to obtain. The use of the model could not be justified in light of the available datasets.

### 2.6.2 HEC-HMS

The Hydrologic Engineering Centre Hydrologic Modeling System (HEC-HMS) is an event based, lumped parameter hydrologic modeling tool which was developed by the U.S. Army Corps of Engineers. It can be used to simulate the precipitation-runoff processes of dendritic watersheds (USACE-HEC, n.d.-a). HEC-HMS can be used to solve a wide range of problems, including, but not limited to, determining large basin river supply, and small and large watershed hydrology (USACE-HEC, n.d.-a).

The simulation methods in HEC-HMS represent the following processes:

- Watershed precipitation and evaporation
- Runoff volume (including direct runoff, overland flow and interflow)
- Baseflow
- Channel Flow (USACE-HEC, n.d.-b)

Depending on the existing available data, users can select different methods of simulation in order to generate runoff hydrographs at different locations within the watershed (McColl and Aggett, 2007). As HEC-HMS is a lumped parameter model, the sub-basins within the model are represented as having homogenous land use, soil types and hydrologic soil groups. HEC-HMS can be used with GIS for data input through the use of an ArcMap extension called HEC-Geo HMS, which allows for convenient input of spatially distributed data such as land use and soil types. However, HEC-HMS cannot simulate water quality, which is important for future work in Jamaica. In addition, it does not allow for the spatial resolution that a distributed model would provide.

### 2.6.3 Soil and Water Assessment Tool (SWAT)

The Soil and Water Assessment Tool (SWAT), is a continuous, long-term, physically based, semi-distributed hydrologic model (Neitsch et al., 2005; Zhang et al., 2008). SWAT can simulate surface and sub-surface flow, soil erosion, nutrient data analysis and sediment deposition, and has been applied worldwide for hydrologic and water quality simulation (Zhang et al., 2008). SWAT has also been applied extensively over a wide range of spatial scales. Gollamudi et al. (2007) applied SWAT to two fields in Southern Quebec, while Zhang et al. (2007), applied SWAT to the 5239 $km^2$ watershed in China for the simulation of daily and monthly stream flows. However, very little hydrologic modelling has been done in Jamaica, and to the author's knowledge the only other documented use of SWAT in Jamaica to this point is by Evelyn (2007). However, there was no need for that model to be calibrated or validated, and the feasibility of using the model to fully simulate the hydrological processes of a watershed has not yet been determined in the island.

SWAT was initially developed to predict the impact of land management practices on water, agricultural chemical yields and sediment in large, complex watersheds (Neitsch et al., 2005). It requires a large amount of specific information such as land use, weather, and soil types. This input data is then used to directly model physical processes such as sediment movement and nutrient cycling (Neitsch et al., 2005). A few of the many advantages of SWAT is that it is computationally efficient, uses readily available inputs, and enables users to study long term impacts (Neitsch et al., 2005).

The 2005 version of SWAT, integrated with the ArcMap 9.3 interface, was used for this study, and is known as ArcSWAT 2005. SWAT incorporates spatially distributed data on landuse, soil, water bodies and digital elevation data into the hydrologic model. It also incorporates land management practices, as well as meteorological data into the model (Narasimhan et al., 2005).

### 2.6.4 ANSWERS-2000

ANSWERS (Areal Non-point Source Watershed Environment Response Simulation) was initially developed in order to evaluate the effects of land management practices on run-off and sediment loss (Beasley et al., 1980). ANSWERS-2000 is a distributed, physically based, continuous model, and is an improvement on the original ANSWERS model. ANSWERS-2000 simulates hydrologic processes including infiltration, surface runoff, crop growth, evapotranspiration and soil moisture movement in the root zone (Bouraoui and Dillaha, 2000). ANSWERS-2000 simulates infiltration through the Green and Ampt method, while evapotranspiration is simulated using Ritchie's method (Ritchie, 1972). However, ANSWERS-2000 does not simulate deep percolation, groundwater flow interflow, or stream base flow (Bouraoui and Dillaha, 2000). Bouraoui and Dillaha (2000) recommend that this model not be used in watersheds where the flow dynamics within the watershed are dominated by sub-surface flow. On days without rainfall, the model uses a 24 hour time step, while during rainfall and runoff events, the model uses a 30 second time step. Cell size may be as small as desired, but may not exceed 1 ha. As the model is distributed, it does require a large amount of input, as do other distributed models such as SWAT. However, the model can be used with a GIS based interface, in order to increase the efficiency of defining inputs (Singh et al., 2006).

ANSWERS-2000 allows the user to model best management practices such as conservation tillage, ponds, grassed waterways and tile drainage (Dillaha, 2003). It can be used as a planning tool and can be used to simulate long term nitrogen and phosphorus transport from rural watersheds (Bouraoui and Dillaha, 2000). ANSWERS-2000 has been used successfully in many parts of the world, from a small watershed in India (Singh et al., 2006) to an agricultural watershed in south western Quebec (Montas and Madramootoo, 1991).

Jamaica's hydrology consists of complex interactions between surface and sub-surface water, especially in the karstic Cockpit Country region of the country. Therefore, any model recommended for use within the Jamaican context must be able to simulate the sub-surface interactions which would take place within these watersheds. Despite the overall suitability of ANSWERS-2000 to this research, its inability to simulate sub-surface flow processes resulted in this model being deemed unsuitable for this research.

### 2.6.5 The Agricultural Non-point Source Pollution Model (AGNPS)

The Agricultural Non-point Source Pollution Model (AGNPS) is a distributed, event based model that was developed by the United States Department of Agriculture (USDA) (Young et al., 1989). This model was developed as a planning tool for developing land management practices that would aim to reduce the transport of sediment and nutrients to water bodies (Mostaghimi et al., 1997). AGNPS simulates runoff volume, peak flow rate and nitrogen and phosphorus transport as a result of the basic model components which include hydrology as well as sediment and chemical transport (Mostaghimi et al., 1997). Like ANSWERS, the watershed is divided into grids, in which the parameters in the grids are homogeneous. The SCS/NRCS (Soil Conservation Service/Natural Resource Conservation Service) curve number (CN) method is used in order to determine the run-off that occurs from each grid (Mostaghimi et al., 1997). It is through the use of the CN that the model is able to evaluate different land management practices, as the CN is a direct representation of these practices. The model simulates soil loss and sediment yield through the use of both the USLE (Universal Soil Loss Equation) as well as the Bagnold stream power equation developed by Bagnold (1966). AGNPS can also be used with a GIS graphical user interface, which again helps in the input of extensive data sets. It has also been used extensively in the U.S., and to some extent worldwide (Cho et al., 2008; Liu et al., 2008; Mankin et al., 1999). However, like ANSWERS, it does not have a framework for simulating sub-surface flows, which is important in the Jamaican context (Mankin et al., 1999). Due to the fact that it is event based, as well as its limitations in simulating sub-surface flow, it was not deemed appropriate for this research.

### 2.6.6 Hydrologic model selection

On review of the various models available for the purposes of this research, the ArcSWAT 2005 interface was deemed to be the most appropriate choice. The SWAT database includes a wide range of crop information which is very useful for modeling land cover in Jamaica. In addition, as SWAT is a continuous, long term, semi-distributed model, it can model the watershed at the spatial resolution necessary to capture the spatial variability of the watershed. In short, the data that is available for Jamaica is sufficient for the use of SWAT. At the same time, SWAT is computationally powerful enough for effective modeling to take place in an efficient manner. The following sections present a more detailed description of the SWAT 2005 model.

## 2.7 Hydrology in SWAT

SWAT divides the watershed into smaller sub-basins for modeling purposes. This is particularly useful when the watershed is very spatially variable, in other words, different areas of the watershed are dominated by different land use, soil types, management practices etc. (Neitsch et al., 2005). As a result, the model can reflect differences in evapotranspiration and soil moisture for different soils and land uses. These sub-basins are then further divided into hydrologic response units (HRUs), which are lumped land areas within the sub-basin that are comprised of unique land cover, soil and management combinations (Neitsch et al., 2005).

The hydrological processes in SWAT are directly modeled with the use of the water balance equation (Neitsch et al., 2005):

$$SW_t = SW_0 + \sum_{i=1}^{t}(R_{day} - Q_{surf} - E_a - w_{seep} - Q_{gw}) \qquad 2.1$$

Where

$SW_t$ is the final soil moisture content (mm $H_2O$),

$SW_0$ is the initial soil moisture content on day i (mm $H_2O$),

$R_{day}$ is the amount of precipitation on day i (mm $H_2O$),

$Q_{surf}$ is the amount of surface runoff on day i (mm $H_2O$),

$E_a$ is the amount of evapotranspiration on day i (mm $H_2O$),

$w_{seep}$ is the amount of water entering the vadose zone of the soil profile on day i (mm $H_2O$), and

$Q_{gw}$ is the amount of return flow on day i (mm $H_2O$).

### 2.7.1 Determination of soil moisture in SWAT

There are several ways in which water is removed from the soil. However, the main way in which this is done is through plant uptake. Evaporation from the soil, as well as percolation past the bottom of the soil profile can also contribute significantly to the removal of water from the soil matrix (Neitsch et al., 2005). Lastly, the lateral flow of water through the soil profile will contribute to stream flow.

SWAT assumes that the water is uniformly distributed within a given layer, and works under the premise that there will be no unsaturated flow in the horizontal direction. However, SWAT does record the water contents of the different soil layers. Hence, SWAT directly simulates saturated flow only, and does not model unsaturated flow in the horizontal direction (Neitsch et al., 2005). This being said, SWAT does model unsaturated flow between layers indirectly with the depth distribution of plant water intake, as well as the depth distribution of soil moisture evaporation (Neitsch et al., 2005). The modeling of percolation, as well as lateral flow is discussed in the following sections as these are the major soil moisture movement processes occurring in the watershed.

<u>Percolation</u>

Percolation is calculated for each layer of the soil profile. SWAT allows water to percolate provided the water content exceeds the field capacity for that layer, and the layer below is not saturated (Neitsch et al., 2005). The equations below describe how the water available for percolation in each layer is calculated:

$$SW_{ly,excess} = SW_{ly} - FC_{ly} \quad \text{if } SW_{ly} > FC_{ly} \qquad 2.2$$

$$SW_{ly,excess} = 0 \quad \text{if } SW_{ly} \leq FC_{ly} \qquad 2.3$$

Where:

$SW_{ly,excess}$ is the drainable volume of water in the soil layer on a given day (mm $H_2O$)

$SW_{ly}$ is the water content of the soil layer on a given day (mm $H_2O$)

$FC_{ly}$ is the water content of the layer at field capacity (mm $H_2O$) (Neitsch et al., 2005)

Storage routing methodology is used for calculating the amount of water that moves from one layer to the underlying layer. This amount of water is calculated using the equation:

$$W_{perc,ly} = SW_{ly,excess} \cdot \left(1 - exp\left[\frac{-\Delta t}{TT_{perc}}\right]\right) \qquad 2.4$$

Where:

$W_{perc,ly}$ is the amount of water percolating to the underlying soil layer on a given day (mm $H_2O$)
$SW_{ly,excess}$ is the drainable volume of water in the soil layer on a given day (mm $H_2O$)
$\Delta t$ is the length of the time step (hrs) and
$TT_{perc}$ is the travel time for percolation (hrs). (Neitsch et al., 2005)

The travel time for percolation is unique to each layer, and is calculated as:

$$TT_{perc} = \frac{SAT_{ly} - FC_{ly}}{K_{sat}} \qquad 2.5$$

Where:

$SAT_{ly}$ is the amount of water in the layer when completely saturated (mm $H_2O$)
$FC_{ly}$ is the water content of the soil layer at field capacity (mm $H_2O$)
And $K_{sat}$ is the saturated hydraulic conductivity for the layer ($mm \cdot h^{-1}$)
(Neitsch et al., 2005)

Water that percolates out of the lowest soil layer enters the vadose zone, which is the unsaturated zone between the bottom of the soil profile and the top of the aquifer.

Lateral flow

Sloan et al. (1983) developed a kinematic storage model, which has been incorporated into SWAT for subsurface flow (Neitsch et al., 2005). This model is based on the mass continuity equation, with the control volume representing the entire hillslope segment. Therefore, sub-surface flow is simulated in a two-dimensional cross-section, along a flow path down the steep hillslope. More information on the use of this model in SWAT can be found in Neitsch et al. (2005).

### 2.7.2 Determination of evapotranspiration in SWAT

Evapotranspiration refers to all processes on the earth's surface by which water is converted to water vapor. Evaporation from the soil, water bodies, and plant canopy are some of the processes which collectively contribute to evapotranspiration (Neitsch et al., 2005). Interestingly, evapotranspiration is also the main process by which water is removed from the watershed. 62% of the precipitation that falls on the earth's continents is lost through evapotranspiration (Dingman, 2002). For the accurate assessment of the impact of land use and climate change on water resources, an accurate estimation of evapotranspiration is critical (Neitsch et al., 2005).

Three methods of calculating evapotranspiration have been incorporated into SWAT: (i) the Penman-Monteith method (Allen, 1986; Allen et al., 1989; Monteith, 1965), (ii) the Preistley-Taylor method (Preistley and Taylor, 1972) and (iii) the Hargreaves Method (Hargreaves and Samani, 1985). The relevance of each method to the model depends not only on the types of inputs available, but also on the climatic conditions of the geographic area in question. The Preistley-Taylor method was deemed the most suitable the purposes of this research, and so it will be discussed below.

<u>Priestley Taylor method in SWAT</u>

The Priestley-Taylor equation, as used in SWAT, is as follows:

$$\lambda E_o = \alpha_{pet} \cdot \frac{\Delta}{\Delta+\gamma} \cdot (H_{net} - G) \qquad 2.6$$

Where:

$\lambda$ is the latent heat of vaporization (MJ $kg^{-1}$)

$E_o$ is the potential evapotranspiration (mm $d^{-1}$)

$\alpha_{pet}$ is a coefficient

$\Delta$ is the slope of the saturation vapor pressure-temperature curve, de/dT (kpa $^{\circ}C^{-1}$)

$\gamma$ is the psychrometric constant (kPa $^{\circ}C^{-1}$)

$H_{net}$ is the net radiation ($MJm^{-2}d^{-1}$)

G is the heat flux density to the ground ($MJm^{-2}d^{-1}$)

<u>Determination of actual evapotranspiration in SWAT</u>

In order to determine actual evapotranspiration, SWAT:

(i) evaporates any rainfall intercepted by the plant canopy

(ii) calculates the maximum amount of transpiration, sublimation and soil evaporation

(iii) calculates the actual amount of sublimation and evaporation from the soil (Neitsch et al., 2005).

## 2.8 Descriptions of central concepts in hydrologic probability

### 2.8.1 Rainfall frequency analysis

Frequency analysis in hydrology allows a set of observed data to be analyzed and evaluated, using efficient and robust statistical techniques. If a sufficiently long record of rainfall depths existed for a particular site, then a frequency distribution could be determined for that site, taking into account changes in land use, and climate change (Stedinger et al., 1993). However, observed rainfall data is usually limited to a specific range in time, and does not cover a long enough time series for the return period of, for example, one hundred years to be estimated. For Jamaica, the longest time period of monthly rainfall is 38 years, and from this observed data, not even a storm with a fifty year return period could be directly estimated. It is particularly in cases like this, when long term data is not available, where a statistical method such as a frequency analysis is extremely useful. The following sections describe the theory behind frequency analyses, as well as the probability distributions that were specifically applied to data in this research.

### 2.8.2 Probability theory

The probability of an event is defined as the relative number of occurrences of an event after a large number of experiment trials. An annual event has a return period (or recurrence interval) of T years if its magnitude is equalled or exceeded once, on the average, every T years (Bedient and Huber, 2002). In hydrology, the probability of exceedance of a hydrologic event is the probability that the event will be equalled or exceeded in any particular year, and is the reciprocal of the return period. The probability of exceedance (F'), can be defined as 1-F, where F is the probability of non-exceedance. The return period, T, can be defined as

$$T = \frac{1}{F'} = \frac{1}{1-F} \qquad 2.7$$

Therefore, a flood with a 50 year return has a probability of 2% of being equalled or exceeded in any particular year. The same concept can be applied to droughts. A return period can be applied to droughts as meaning "equal to or more severe than" (Bedient and Huber, 2002).

### 2.8.3 Probability distributions

It is important to recognize that the true probability distributions applied to a rainfall event are in actuality not known. Even if there was a situation where the exact distribution were known, the amount of parameters which would be associated with that distribution would be too many to make the distribution of any practical use (Stedinger et al., 1993). The practical approach therefore is to find a simple, yet accurate distribution which describes the rainfall event. There are several probability distributions which have been developed in order to represent different events. However, the three which will be of focus in this manuscript are the Gamma Distribution, Generalized Extreme Value Distribution and Log-normal distribution. In order for these specific probability distributions to be understood, the concepts of probability distribution functions (PDFs) and cumulative distribution functions (CDFs) need to be understood. For detailed descriptions of the concepts of PDFs and CDFs, refer to Appendix A. For an even more detailed description of these functions, refer to Chin (2006), as well as Stedinger et al. (2006).

### 2.8.4 Fitting distributions to data

The distribution functions described above are simply a few of many existing functions used in hydrology. The question inevitably arises as to which distribution is best suited to the hydrological phenomenon being analyzed. By the use of the term suited, or suitable, the authors refer to the fact that the distribution should give reasonably accurate and robust estimates of hydrologic risk. One of the most useful and practical methods is probability plotting, which visually reveals the most suitable distribution for a particular dataset. They allow the hydrologist to see if the chosen distribution is consistent with the data (Stedinger et al., 1993). Another method of assessing which fit is the best is through use of mathematical and statistical software. Matlab ™ is an example of such software. Both of these methods, can be coupled with goodness of fit tests, in order to quantitatively assess which distribution is the most suitable.

Plotting positions and probability plots

The concept behind doing a graphical evaluation of a selected distribution, is that if the CDF is plotted vs. the magnitude of the random variable, then the theoretical fit would be a straight line. This has to be done on plotting paper which has been specially scaled for the specific distribution. These papers are generally commercially available (Bedient and Huber, 2002).

There are several different plotting positions which have been developed for this purpose. The Weibull plotting position, as well as the Gringorten position will be explained in detail in this section. In order for these formulas to be used, the data must be ranked in order of decreasing magnitude. As such, the return period will describe the probability of exceedance. However, in special cases, where the data is being assessed for drought management purposes, or low flows, the data can be ranked in order of increasing magnitude, resulting in the return period describing the probability of being 'equal to or more severe than'. The Weibull plotting formula is the most common position, and is described as:

$$T = \frac{n+1}{m} \tag{2.8}$$

and

$$F = 1 - \frac{m}{n+1} \tag{2.9}$$

(Bedient and Huber, 2002)

where n is the number of years on record, and m is the rank of the data.

The Gringorten plotting position formula (Gringorten, 1963) is as follows:

$$T = \frac{n+1-2a}{m-a} \tag{2.10}$$

and

$$F = 1 - \frac{m-a}{n+1-2a} \tag{2.11}$$

(Bedient and Huber, 2002)

where m and n are as defined above, and a is parameter which depends on the distribution. It is equal to 0.375 for the normal or lognormal distribution, and 0.4 in a situation where the exact distribution is unknown.

<u>The use of Matlab ™</u>

There are several statistical software which can be used for effective and accurate distribution fitting. The Matlab™ software was chosen due to its powerful computational framework, as well as the fact that is an extremely versatile tool. In addition, it does not require coding for this particular function, and instead functions through a graphical user interface (GUI). In essence, it is a comprehensive and powerful piece of software, and was deemed very appropriate for this research. Another software which exists is the SAS (Statistical Analysis System) software, which requires code, and does not have the GUI that Matlab™ has for this particular function. The GUI tool that Matlab™ has is called the Distribution Fitting Tool, which can be used for fitting univariate distributions to data. This tool allows for several distributions to be fitted to data, including, but not limited to: lognormal, normal, Weibull, GEV, Gamma, logistic, exponential, binomial, non-parametric and Poisson distributions.

### 2.8.5 Assessment of fitted distributions

A goodness of fit test allows for a quantitative assessment of the best fit. There have been many methods developed in order to assess goodness of fit. The two that will be addressed in this section are the use of hypothesis tests, as well as the CDF comparison tests.

Hypothesis tests and confidence limits

Confidence limits are control curves plotted on either side of the fitted CDF. The theory behind them is that, if the data belong to the fitted distribution, a known percentage of the data points should fall between the two curves (Bedient and Huber, 2002). These control curves can be plotted through the use of goodness of fit hypothesis tests, such as the Kolmogorov-Smirnoff test. The chi-square hypothesis test is usually applied to bins (data intervals), and is consequently not used in plotting confidence limits.

Kolgomorov-Smirnov (KS) test

The KS test is a non-parametric test, meaning that no parameters of the theoretical probability distribution need to be derived from the observed data (Chin, 2006). This test can be used to plot confidence limits, or as a deterministic test. A confidence interval on the CDF can be plotted as follows:

Let $F_p$ be the predicted value of the CDF. Therefore, a confidence interval on the CDF can be constructed such that:

$$\text{Prob}\,(F \leq F_u) = \text{Prob}\,(F \leq F_p + KS) = 1 - \alpha \qquad 2.12$$

and

$$\text{Prob}\,(F_l \leq F) = \text{Prob}\,(F_p - KS \leq F) = 1 - \alpha \qquad 2.13$$

(Chin, 2006)

Where KS is the Kolmogorov-Smirnov statistic at confidence level $\alpha$, and subscripts *u* and *l* mean upper and lower respectively (Chin, 2006).

The KS test can also be used as a deterministic test. The procedure is as follows, and is obtained directly from Chin (2006):

1) Let $P_X$ be the specified theoretical cumulative distribution function under the null hypothesis
2) Let $S_N$ be the sample cumulative distribution function based on N observations. For any observed *x*, $S_N = k/N$, where *k* is the number of observations less than or equal to *x*.
3) Determine the maximum deviation, D, defined by

$$D=\max|P_X - S_N| \qquad 2.14$$

4) If, for the chosen level of significance, the observed value D is greater than or equal to the critical value of the KS statistic, the hypothesis is rejected.

Values of the KS statistic, for both methods, can be obtained from tables in most hydrology texts, however, Bedient and Huber (2002) and Chin (2006) are highly recommended to the reader.

<u>Chi-square test</u>

"Based on sampling theory, it is known that if the N outcomes are divided into M classes, with $X_m$ being the number of outcomes in class m, and $p_m$ being the theoretical probability of an outcome being in class *m*, then the random variable

$$\chi^2 = \sum_{m=1}^{M} \frac{(X_m - Np_m)^2}{Np_m} \qquad 2.15$$

has a chi-square distribution" (Chin, 2006)

The null hypothesis is taken as $H_0$: The samples are drawn from the proposed probability distribution. This null hypothesis is accepted at the $\alpha$ significance level if $\chi^2 \epsilon [0, \chi^2_\alpha]$. The effectiveness of this test is diminished however, if the number of bins is less than 5 (Chin, 2006).

Heuristic goodness of fit test

There are several heuristic goodness of fit tests, however, the one which will be mentioned very briefly here is a test developed by Benson (1968). This test quantitatively compares the fitted CDF to the actual CDF, by determining the absolute values of deviations between the plotted and fitted CDF, and is performed over intervals.

## CONNECTING TEXT TO CHAPTER 3

This manuscript is co-authored by my supervisor Dr. Chandra A. Madramootoo. All literature cited in this chapter is listed in the reference section at the end of this chapter, as well as at the end of this thesis. Chapter 3 describes the determination of irrigation requirements for Savanna-la-mar, Beckford Kraal and Serge Island. This chapter provides monthly irrigation demand values for both sugarcane and vegetables, which were calculated based on average monthly soil moisture values. These values are meant to provide a convenient reference for irrigation planning during average soil moisture conditions.

## NOMENCLATURE FOR CHAPTER 3

$\alpha$: Confidence level

a: A parameter in the Gringorten plotting formula
CDF: Cumulative Distribution Function
$D_a$: Depth of water supplied per irrigation application

$ET_c$: Monthly actual crop evapotranspiration

$ET_p$: Monthly potential evapotranspiration

$f$ : A correction factor which depends on the depth of the irrigation water supplied per application (-)

F': Probability of exceedance
F'u: Upper limit of probability of exceedance on confidence interval
F'l: Lower limit of probability of exceedance on confidence interval
FC: Field Capacity
GDP: Gross Domestic Product
GEV: Generalized Extreme Value
$IR$: Irrigation Requirement

Ge: Monthly Groundwater contribution from water table

KS: Kolgomorov-Smirnoff
$L_s$ : Moisture loss from the surface layer
$L_u$: Moisture loss from the underlying soil
LR: Monthly Leaching Requirement
m: Rank of the data for frequency analysis
mm: Millimeter
n: Number of years of data on record for frequency analysis
P: Monthly precipitation
Pe: Monthly Effective Rainfall

PDF: Probability Distribution Function
$S'_s$: Available moisture in the surface layer at the start of the month

$S'_u$: Available moisture stored in the underlying soil at the start of the month

SWa: Plant Available Water stored in the soil at the end of each month

T: Return period

$w_{ac}$: Available water capacity of the soil

WP: Wilting Point

# CHAPTER 3: Determination of irrigation requirements for vegetables and sugarcane

Johanna Richards, Chandra A. Madramootoo

**ABSTRACT**

Currently, only 10% of the cultivated lands in Jamaica are irrigated, and as a result farmers are highly dependent on seasonal rainfall. For this reason, a study was undertaken in order to determine monthly irrigation requirements for three study sites, for both vegetables and sugarcane. In addition, the cumulative frequencies of monthly and seasonal rainfall depths were analyzed, and this information used to develop monthly rainfall values, as well as seasonal rainfall values for different return periods for the sites. This information is meant to provide a foundation for irrigation planning and water management strategies during water scarce conditions.

**Keywords:** Irrigation Requirements, Water Scarcity Planning, Gamma Distribution, Generalized Extreme Value Distribution, Rainfall Frequency Analysis

## 3.1 Introduction

Agriculture in Jamaica is heavily dependent on rainfall, where approximately only 10% of the cultivated lands are irrigated. The main irrigated crop is sugar cane, which accounts for 70-80% of the irrigated land. The majority of irrigation systems are located in areas characterized by dry climatic conditions (effective rainfall normally below 1000 mm/year) (Ministry of Water and Housing, 2004). As a result, plant/harvesting cycles typically revolve around the wet and dry seasons. Some estimates indicate that as much as 95% of all domestic agricultural production is rainfed (Chen et al., 2005). One result of this seasonality in production is the ensuing periods of gluts and shortages, especially for vegetable crops (Weis, 2004). Water has been identified as one of the key environmental constraints to production. As rainfall governs crop yields and affects the types of crops which can be grown, this high dependence on rainfall can have significant effects on crop production. In light of this, the need for irrigation planning and expansion has been acknowledged by government agencies and researchers alike (NIC, 2009; Weis, 2004). It is imperative however, that farmers be provided with the tools to effectively implement their irrigation management plans. Such tools include irrigation demand guidelines.

The agricultural sector is facing considerable competition for water resources due to increased urban development, as well as increased tourism. In addition, the potential impacts of climate change add pressure to an already over-stressed system. As a result, efficient irrigation management systems are instrumental to water resources management. The determination of irrigation demands requires knowledge of different components of the water balance, including actual evapotranspiration, available soil moisture, and effective precipitation. Unfortunately, no previously published work has been found which addresses these issues for these areas, and so this chapter describes the determination of each of these components, and outlines the irrigation requirements which have been calculated for both sugarcane and vegetables.

## 3.2 Materials and methods

### 3.2.1 Study area description

Three sites: Savanna-la-mar in the parish of Westmoreland, Beckford Kraal in the parish of Clarendon, and Serge Island in the parish of St. Thomas were used in this study (Figure 3.1). These sites were selected because there is historical rainfall data spanning a minimum period of 30 years. Each site has distinctly different soil characteristics and farming practices. The soils have great spatial variability within all three parishes. For the purposes of this research, the soil which dominated the 500 m radius of each climate station was used. The basic characteristics of each site are described as follows.

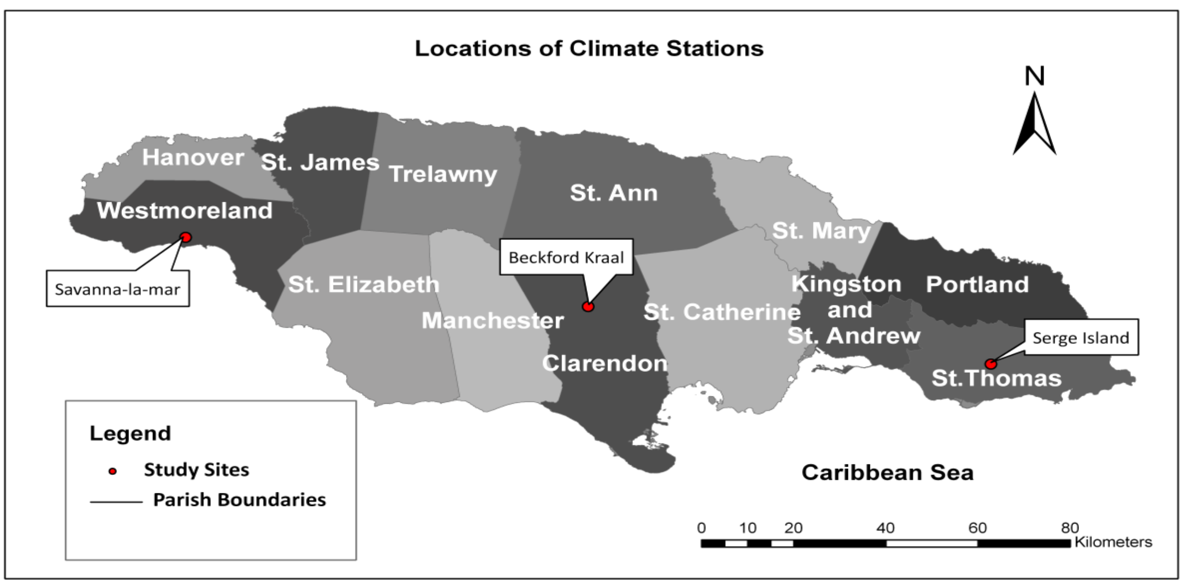


**Figure 3.1: Location of climate stations**

Savanna-la-mar has three distinct growing seasons. These growing seasons range from September to December, January to April, and May to August. Crops such as Irish potatoes (*Solanum tuberosum*), carrots (*Daucus carota*), tomatoes (*Lycopersicon esculentum*), sweet peppers (*Capsicum annuum*), cauliflower (*Brassica oleracea botrytis*) and cabbage (*Brassica oleracea capitata*) are grown during the months of September to April in two rotations of three to four months each, while perennial crops such as pineapples (*Ananas comosus*), papayas (*Carica papaya*), plantains (*Musa paradisiaca*) and bananas (*Musa sapientum*) are harvested during the summer months (May to August) (Mitchell , 2010, *personal communication*). Loam soil is the dominant soil type.

At Beckford Kraal, vegetable crops are rotated three to four times throughout the entire year, despite seasonal variations in rainfall (Stone 2010, *personal communication*). The crops grown are callaloo (*Amaranthus viridis*), carrots, cauliflower, lettuce, pak-choy (*Brassica rapa var. chinensis*), cabbage and pumpkins (*Cucurbita pepo*) etc. Clay is the dominant soil type. At Serge Island, there are also multiple rotations of the vegetable crops throughout the entire year (Hemans , 2010, *personal communication*). These crops include carrots, tomatoes, pumpkin, cabbage etc. Sandy loam is the dominant soil type. Note that sugarcane can be grown year round at all three locations. The typical harvesting time can range anywhere from December to April.

### 3.2.2 Determination of soil moisture

A conceptual soil moisture model based on the water balance, was used for this research (Chin, 2006). The soil moisture model is based on a monthly accounting of the water balance. The model splits the soil column into two layers: an upper and lower soil layer. The following equations are used to account for available soil moisture:

$$L_s = \min\,[S'_s, (ET_p - P)] \qquad 3.1$$

$$L_u = (ET_p - P - L_s)\frac{S'_u}{w_{ac}}, \text{ provided that } L_u \leq S'_u \qquad 3.2$$

$L_s$ is the moisture loss from the surface layer, $S'_s$ is the available moisture in the surface layer at the start of the month, $ET_p$ is potential evapotranspiration, P is monthly precipitation, $L_u$ is the moisture loss from the underlying soil, $S'_u$ is the available moisture stored in the underlying soil at the start of the month, and $w_{ac}$ is the available water capacity of the soil (Chin, 2006). This model is based on the assumption that as the amount of water within the soil column decreases, the rate at which it can be removed from the soil also decreases. As this model determines available soil moisture, it is inherently bound between the field capacity (FC) of the soil, and the wilting point

(WP) of the soil. The values of each of these parameters for each soil are shown in Table 3.1 below. These values were obtained from Schwab et al. (1993), and are generic values based on soil textural information. The values were converted from volumetric water contents to depths, and so the values listed in Table 3.1, and hence all values of available soil moisture listed in this chapter, are soil moisture depth per metre of soil.

**Table 3.1: Soil moisture parameters**

| Study Site | Field Capacity (mm) | Wilting Point (mm) | Available Water Capacity (mm) |
|---|---|---|---|
| Savanna-la-Mar | 310 | 140 | 170 |
| Beckford Kraal | 440 | 210 | 230 |
| Serge Island | 210 | 90 | 120 |

The simulation was started November 1 for both the Savanna-la-mar and Serge Island Sites, as this is at the peak of the wet season. This being the case, it was assumed that the soil was at field capacity during this time. However, for the Beckford Kraal site, the simulation was started in June 1, due to the fact that during the period September to November through the period of 1970 to 1980, a deficit was seen between total monthly precipitation and potential evapotranspiration, and it would not have been reasonable to assume that the soil was at field capacity during these months. As such, it was assumed that the soil was at field capacity on June 1.

### 3.2.3 Rainfall frequency analysis

The assessment of rainfall events can be performed through the use of statistical techniques, with the application of probability theory. Probability and cumulative distributions are tools which can be applied in order to determine the monthly and seasonal rainfall depths which are expected for various return periods. Therefore, a frequency analysis was done for each month, using the 38 year monthly rainfall data for each station. This was done in order to determine the precipitation values for each month associated with different return periods. The most suitable probability distribution function (PDF) was fitted to the data, using the Matlab™ software, which was used for the construction of probability plots, as well as curve fitting. A heuristic measure of goodness of fit test was done, similar to that proposed by Benson (1968) as described in Bedient and Huber (2002).The cumulative distribution function (CDF) for each likely fit was compared to the CDF for the actual data, and the fit with the least average standard error was used. The Kolgomorov-Smirnoff (KS) test was then used to verify the goodness of fit by ensuring that the selected PDF represented the data within a 5% confidence level. The KS test is non-parametric, meaning that no parameters of the theoretical probability need to be derived from the observed data (Chin, 2006). If, for a chosen theoretical PDF, the maximum deviation between any observed frequency and theoretical frequency is greater than the critical KS statistic for a particular level of significance, the hypothesis that the theoretical PDF fits the observed data is rejected.

Seasonal rainfall analysis

Using the same 38 year monthly rainfall data available for each station, the total seasonal rainfall was determined for each station. This was done for the season January to April, and the season May to August. The season of September to December was not analyzed as this is, on average, the wettest season of the year. In order for an analysis to be done of seasonal rainfall, the typical method of using the plotting positions was modified. Usually, the data is ranked in order of decreasing magnitude, with the return period referring to “equal to or exceeding”. However, for the seasonal rainfall values to be relevant in the context of water scarcity management, the return period had to refer to “equal to or less than”. To this end, the data was ranked in order of increasing magnitude, while using the Gringorten plotting position (Gringorten, 1963). This plotting position was chosen as it is a generalized form, and does not exclude many of the distributions that the Weibull formula does. This plotting position is as follows:

$$T = \frac{n+1-2a}{m-a} \quad 3.3$$

and

$$F' = 1 - \frac{m-a}{n+1-2a} \quad 3.4$$

T is the return period, F’ is the probability of exceedance, n is the number of years on record, and m is the rank of the data. It was determined that the log-normal distribution was the most suitable for the seasonal rainfall, within a 95% confidence level (5% level of significance). A goodness of fit test was performed using control curves plotted on either side of the fitted CDF. These curves can be plotted as follows:

Let $F'_p$ be the predicted value of the CDF. So, a confidence interval on the CDF can be constructed such that

$$\text{Prob}\,(F' \leq F'_u) = \text{Prob}\,(F' \leq F'_p + \text{KS}) = 1-\alpha \quad 3.5$$

and

$$\text{Prob}\,(F'_l \leq F') = \text{Prob}\,(F'_p - KS \leq F') = 1-\alpha \quad 3.6$$

(Chin, 2006)

KS is the Kolmogorov-Smirnov statistic at confidence level $\alpha$, and subscripts *u* and *l* mean upper and lower respectively (Chin, 2006).

### 3.2.4 Determination of irrigation requirements

The irrigation requirement was derived from the relationship modified from Savya and Frenken (2002):

$$IR = ET_c - (Pe + Ge + SWa) + LR_{mm} \quad 3.7$$

(Savya and Frenken, 2002)

where:

$IR$ = Irrigation Requirement (mm)

$ET_c$ = Monthly Crop Evapotranspiration (mm)

Pe = Monthly Effective Rainfall (mm)

Ge = Monthly Groundwater contribution from water table (mm)

SWa = Plant Available Water stored in the soil at the end of each month (mm)

LR = Monthly Leaching Requirement (mm)

The determination of each of the above parameters will be discussed in the following sections.

Crop Evapotranspiration ($ET_c$)

The Class 'A' pan evaporation was used to determine crop evapotranspiration for both sugarcane and vegetables. For the purposes of this study, vegetables represent cabbages, carrots, cauliflower and lettuce. Ten year average monthly pan evapotranspiration values were available for each area, and these were used, along with the relevant pan coefficient and Kc values (Table 3.2) to determine ETc values for each crop. The Kc values used in this study were for crops in humid climates ($RH_{min}$> 70 %). A graphical method was used (Figure 32 in Allen et al. (1998)) in order to determine the Kc values for humid climates. There is a jump from a Kc value of 0.3 in April to 0.95 in May for sugarcane, as April is the end of the harvesting period and May is the beginning of the initial growth period. A pan coefficient of 0.85 was used and chosen based on data published by Allen et al. (1998). No relative humidity data was easily available for any of the climatological stations used in this study. However, relative humidity data was available for a few other stations in other parts of the island. The relative humidity for all other stations remained above 70 % for all months of the year. In addition, a light wind speed of < 2 m/s was assumed for all three areas, as this is a reasonable assumption to make for areas having a high relative humidity (Allen et al., 1998). It is for these reasons, that the pan coefficient of 0.85 was deemed suitable for use, in all three areas, and for all months of the year.

**Table 3.2: Crop Kc values for vegetables and sugarcane (Allen et al., 1998)**

| Month | | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Crop Kc | Vegetables | 0.64 | 0.97 | 0.97 | 0.87 | 0.64 | 0.97 | 0.97 | 0.87 | 0.64 | 0.97 | 0.97 | 0.87 |
| | Sugarcane | 0.62 | 0.62 | 0.32 | 0.3 | 0.95 | 0.95 | 0.95 | 0.92 | 0.92 | 0.92 | 0.92 | 0.62 |

<u>Effective rainfall (Pe)</u>

In order to determine the irrigation requirements for each study area, the rainfalls associated with 80% and 90% probability of exceedance were found for each month, for each station. These values were chosen based on recommendations by Savya and Frenken (2002). The rationale behind these recommendations is that it is reasonable to assume that an 80% probability of exceedance provides a reasonable estimate of the minimal amount of rainfall which is likely to occur. The rainfall associated with the 90% probability of exceedance was used for the months of December to April, as these months experience the least amount of rainfall and crops during these months are the most vulnerable to the lack of rainfall. For the months of May to November however, the rainfall values with an 80% probability of exceedance were used. In order to determine monthly effective rainfall, the following empirical equation was used (Bos et al., 2009):

$$Pe = f \times (1.253P^{0.824} - 2.935) \times 10^{0.001\,ET_c} \quad 3.8$$

(Bos et al., 2009)

where,

Pe = the effective precipitation per month (mm/month)

$f$ = a correction factor which depends on the depth of the irrigation water supplied per irrigation application (-)

P = the precipitation per month (mm/month)

$ET_c$ = the total crop evapotranspiration per month (mm/month)

$f$ is calculated as follows:

$$f = 0.133 + 0.201 lnD_a \quad if\ D_a < 75\ mm/application \quad 3.9$$

and

$$f = 0.946 + 7.3 \times 10^{-4} \times D_a \quad if\ D_a \geq 75mm/application \qquad 3.10$$

(Bos et al., 2009)

$D_a$ is the depth of water supplied per irrigation application. This method is based on the assumption that a high storage capacity within the soil indicates a relatively high effectiveness of precipitation (Bos et al., 2009). Therefore, the depth of irrigation water applied per irrigation turn is assumed to be equal to the readily available soil water. $D_a$ was assumed to be 170 mm for Savanna-la-mar, 230 mm for Beckford Kraal, and 120 mm for Serge Island (as shown in Table 3.1).

Groundwater contribution from water table

Groundwater table data has been collected by the Water Resources Authority of Jamaica for different locations within the island, and is available on their website at www.wra.gov.jm. However, no recent water table levels which were part of a historical time series were available for the study areas. As a result, it was deemed as necessary to ignore groundwater contribution to crop water requirements.

Leaching requirement (LR)

In order to manage high salt conditions in the root zone, extra water can be used for irrigation in a process called leaching (Savya and Frenken, 2002). The leaching requirement is the excess amount of irrigation water used for this process, and depends on the irrigation water salinity, and the crop tolerance to salinity. In addition, the salinity in the soil also depends on irrigation practices and soil conditions. This leaching requirement is location specific. Due to the fact that the soils in the study areas do not have high salinities, the leaching requirement was ignored for the purposes of these calculations. It must be considered however that once irrigation takes place in these areas over a significant period of time, then the leaching requirement might have to be considered. The applicable data would have to be obtained for accurate determination of the leaching requirement.

## 3.3 Results

### 3.3.1 Exceedance probabilities of monthly rainfall

Monthly data were fitted to either the Gamma or the GEV distribution. The GEV was, in general, found to be the most suitable fit for the monthly rainfall totals, for all three study areas, for all months except the months of May and June for Savanna-la-Mar, the month of April for Beckford Kraal, and the months of June and November for

Serge Island. Both of these theoretical PDFs fit the observed data within a 5% level of significance. Figures 3.2 to 3.4 show monthly rainfall for different probabilities of exceedance for all three study areas. The probability of exceedance is the probability that a certain depth of rainfall is equalled or exceeded.

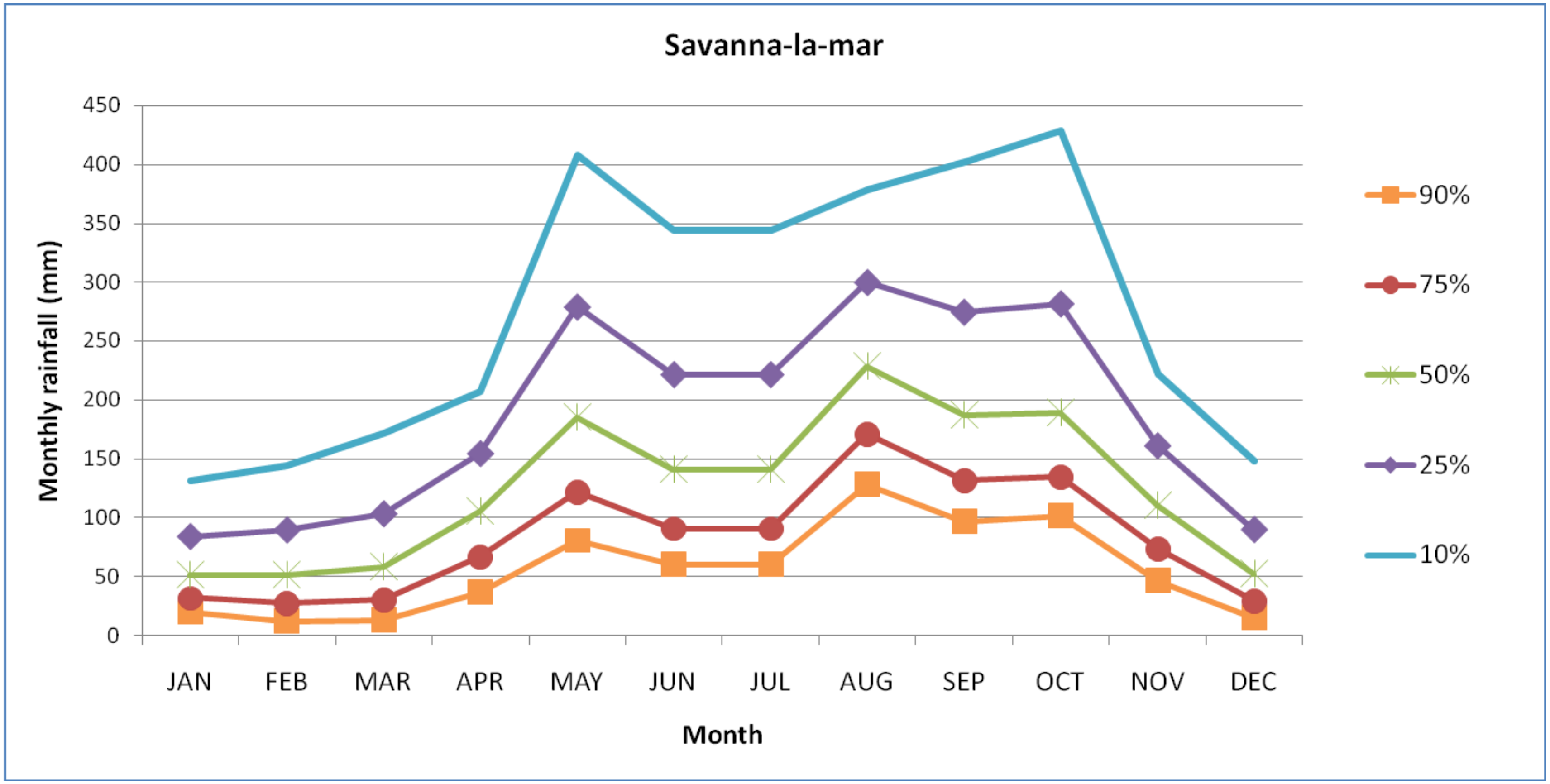


**Figure 3.2: Rainfall depths for 10, 25, 50, 75 and 90% probabilities of exceedance for Savanna-la-Mar**

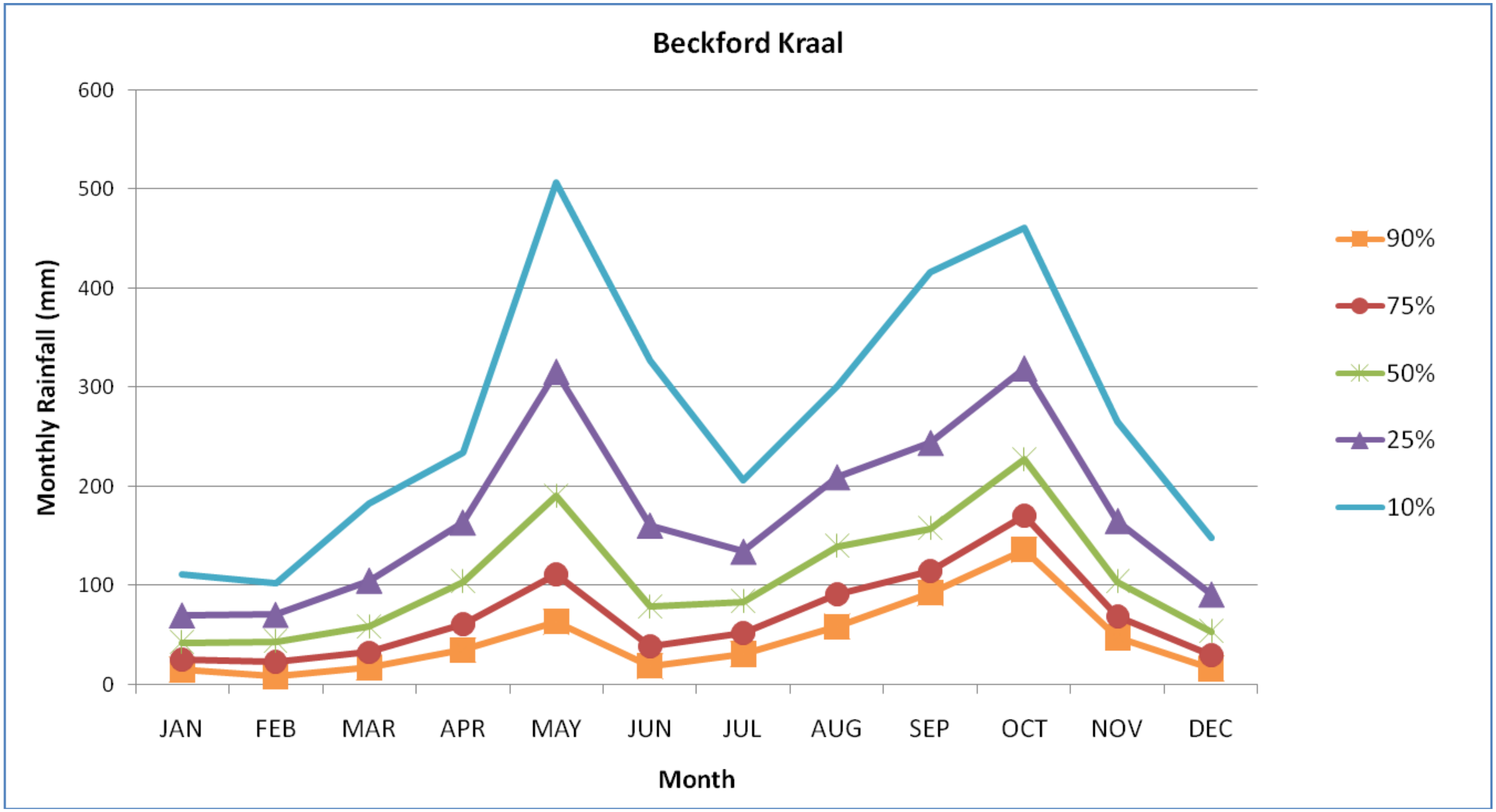


**Figure 3.3: Rainfall depths for 10, 25, 50, 75 and 90% probabilities of exceedance for Beckford Kraal**

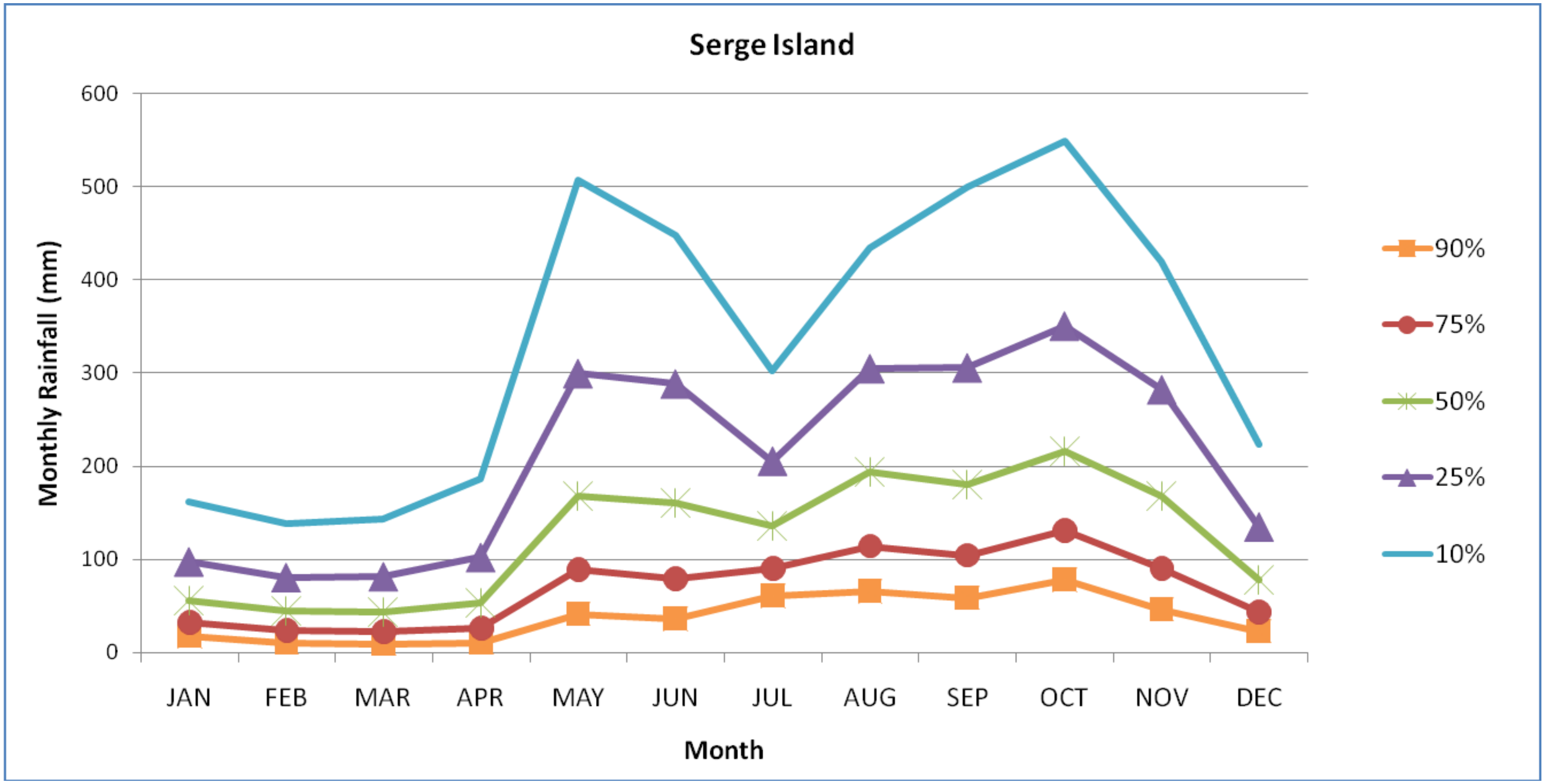


**Figure 3.4: Rainfall depths for 10, 25, 50, 75 and 90% probabilities of exceedance for Serge Island.**

Monthly rainfall

The monthly rainfall was then obtained for each area at 80% and 90% exceedance probabilities, and the rainfall depths for these probabilities are shown in Table 3.3 below. The monthly rainfalls for cumulative probabilities ranging from 1% to 99% are shown in Tables A.1 to A.3.

**Table 3.3: Monthly rainfall for Savanna-la-mar, Beckford Kraal and Serge Island for exceedance probabilities of 80 and 90%**

| | | Monthly Rainfall (mm) | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Location** | **Exceedance Probability (%)** | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
| **Savanna -la-Mar** | 90% | 20 | 12 | 13 | 37 | 81 | 60 | 60 | 128 | 96 | 102 | 47 | 15 |
| | 80% | 28 | 23 | 25 | 58 | 109 | 81 | 81 | 159 | 121 | 124 | 66 | 25 |
| **Beckford Kraal** | 90% | 16 | 9 | 18 | 35 | 64 | 19 | 31 | 59 | 93 | 136 | 48 | 16 |
| | 80% | 23 | 19 | 28 | 53 | 97 | 33 | 45 | 81 | 108 | 160 | 62 | 26 |
| **Serge Island** | 90% | 17 | 11 | 9 | 10 | 41 | 36 | 61 | 66 | 59 | 78 | 46 | 23 |
| | 80% | 27 | 19 | 18 | 21 | 74 | 65 | 81 | 99 | 90 | 115 | 76 | 37 |

### 3.3.2 Exceedance probabilities of seasonal rainfall

The seasonal rainfall was fitted to the lognormal theoretical distribution, again within a 5% level of significance. Table 3.4 shows the seasonal rainfall expected for different probabilities of occurrence. Again, note that because the data was ranked in order of increasing magnitude in a modified application of the Gringorten plotting formula, the expected seasonal rainfall depths increase as the probability of occurrence increases.

**Table 3.4: Seasonal rainfall frequency analysis results**

| Recurrence Interval Indicators | | Total Seasonal Rainfall (mm) | | | | | |
|---|---|---|---|---|---|---|---|
| | | January to April | | | May to August | | |
| Return Period | Probability of Occurrence | Serge Island | Beckford Kraal | Savanna-La-Mar | Serge Island | Beckford Kraal | Savanna-La-Mar |
| **2** | 50% | 250 | 275 | 300 | 800 | 600 | 780 |
| **2.5** | 40% | 211 | 250 | 265 | 720 | 530 | 690 |
| **3.3** | 30% | 180 | 230 | 230 | 640 | 470 | 650 |
| **5** | 20% | 150 | 195 | 200 | 560 | 400 | 590 |
| **10** | 10% | 112 | 162 | 160 | 470 | 330 | 510 |
| **20** | 5% | 90 | 140 | 135 | 400 | 280 | 450 |
| **50** | 2% | 70 | 120 | 110 | 340 | 230 | 390 |
| **100** | 1% | 59 | 106 | 96 | 300 | 204 | 360 |

### 3.3.3 Irrigation demands

The irrigation requirements are shown in Table 3.5 below. The table shows the monthly requirements for both sugarcane and vegetables, for all three study locations for average monthly soil moisture. The irrigation requirements were calculated using equation 3.7, with all parameters calculated as shown in the previous chapters. Please refer to Tables A.7 to A.9 for irrigation requirements for localized, sprinkler and surface irrigation all three study areas. The irrigation efficiencies used in the calculations of the localized, sprinkler and surface irrigation requirements are shown in Table A.6 (Savya and Frenken, 2002).

**Table 3.5: Irrigation demands for vegetables and sugar cane for Savanna-la-mar, Beckford Kraal and Serge Island**

| Climate Station | Crop | Irrigation Requirement at end of month (mm) | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
| **Savanna-la-Mar** | Vegetables | 0 | 59 | 90 | 52 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 3 |
| | Sugarcane | 0 | 17 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **Beckford Kraal** | Vegetables | 0 | 0 | 27 | 16 | 0 | 0 | 29 | 55 | 0 | 0 | 0 | 0 |
| | Sugarcane | 0 | 0 | 0 | 0 | 0 | 0 | 23 | 59 | 0 | 0 | 0 | 0 |
| **Serge Island** | Vegetables | 29 | 80 | 117 | 133 | 0 | 43 | 63 | 9 | 0 | 0 | 0 | 30 |
| | Sugarcane | 27 | 39 | 23 | 34 | 50 | 45 | 66 | 23 | 0 | 0 | 0 | 0 |

## 3.4 Discussion

### 3.4.1 Irrigation requirements

The results in Table 3.5 show that sugarcane in Serge Island needs to be irrigated for the entire year except for September to December, for typical soil moisture conditions. For vegetables, May, September, October and November are the only months that do not require irrigation. According to the historical trends, the period of December to April actually receives the least amount of rainfall. This is also the period during which cane is reaped, as it allows for the cane to sweeten. The early growth of sugar cane typically receives a boost with the April - June rains. The fastest growth of the sugar cane then occurs in the July to September period (Chen et al., 2005). During this period, lack of rains can seriously affect growth. Good rains during this period will seriously improve growth, even compensating for lack of rainfall in earlier seasons. Typical harvesting times are in the period December to April, as the industry takes advantage of the cool and dry period. There are four climate-related stresses which can lead to a poor harvest of sugarcane (Chen et al., 2005). These are (i) rainfall in November to May being below normal (ii) rainfall in July to September being below normal (iii) rainfall and temperatures being above normal during November to March, and (iv) excessive spring rains in poorly drained soils in flood prone areas. Interestingly, the occurrence of drought might have a negative or positive effect on the sugar industry, depending on which stage of the growth cycle it occurs at.

At Beckford Kraal, the months of March, April, July and August require irrigation for vegetables. Only the months of July and August need irrigation for sugarcane. For Savanna-la-mar, only the months of December, as well as February through to April require irrigation for vegetables, while only February requires irrigation for sugarcane. There is clearly a much larger need for irrigation in Serge Island than in the other two locations. This is especially interesting considering the fact that Serge Island and Beckford Kraal receive similar amounts of rainfall. Figures 3.2 to 3.4 demonstrate that Beckford Kraal and Serge Island receive more rainfall than Savanna-la-mar, with the 10% probability of exceedance peaking at approximately 500 mm in the months of May and September. Savanna-la-mar receives the least amount of water, the 10% probability of exceedance peaking at approximately 400 mm during the months of May and September.

The fact that Serge Island requires the most irrigation is most likely related to the fact that the soil is sandy loam, and demonstrates the importance the soil type plays in irrigation planning. This soil has the smallest water holding capacity, and drains very easily. The soils in the other two sites have a larger water holding capacity, as they are loam and clay. It is for this reason, that care should be applied when applying these results to other agricultural areas outside the study areas.

It is acknowledged that there is a wide range of soil types that are present in the study areas. Until further research takes place, these results can act as a guide for other soils within the relevant parishes. In addition, the spatial variability of the rainfall is very high, which again affects the applicability of the research over large land areas. Based on these limitations, it would be very beneficial if this research was expanded to take into account the other soils and rainfall variability within the parishes.

Seasonal rainfall analysis

The seasonal rainfall analysis was performed so that the lowest depths of rainfall would have the smallest probability of occurrence. As expected, the summer months (May to August), have higher depths of seasonal rainfall. Consequently, for the same probability of occurrence, a higher amount of rainfall will be achieved for the season May to August, than for the season January to April. For the "one hundred year" return period, during the months of January to April, Serge Island receives the smallest amount of rainfall. On the other hand, during the one hundred year return period for the months of May to August, Beckford Kraal receives the least amount of rain. This shows that on a seasonal basis, the rainfall characteristics can vary tremendously. Different planning strategies would therefore be needed not only for each location, but for each season.

## 3.5 Conclusions

Monthly regional irrigation requirements were calculated for sugarcane and vegetable crops for Savanna-la-mar, Beckford Kraal and Serge Island. Each study site is unique in its irrigation requirements, which highlights the climatic and soil variability across the island. Serge Island has the highest irrigation demand of all three locations, and this is most likely due to the fact that the dominant soil at that site is sandy loam. However, all three sites are similar in their need for irrigation during the months of March and April for vegetables, signifying that this is a universally dry period across the island. Lastly, a seasonal rainfall analysis was performed for the seasons of January to April, and May to August for the sites, the results of which are also published in this manuscript. The analysis was performed in order to determine the return periods of low seasonal rainfall depths. As expected, the season of May to August receives more rainfall than that of January to April, and again, each site is unique in terms of its characteristics.

### 3.6 References


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## CONNECTING TEXT TO CHAPTER 4

The chapter is a manuscript co-authored by my supervisor Dr. Chandra Madramootoo, as well as Adrian Trotman, the Chief of Applied Meteorology and Climatology at the Caribbean Institute of Meteorology and Hydrology. All literature cited in this chapter is listed in the reference section at the end of this chapter, as well as at the end of this thesis.

Chapter 4 covers the development of the SPI and the NDVI for the sites, as well as the correlation of these indices to soil moisture. A description of the development of both indices, as well as the calculation of soil moisture is included in this chapter. The developed relationships between the indices and soil moisture are presented. The irrigation results presented in Chapter 3 were obtained using the monthly soil moisture for each month, averaged over a 30 year period. However, during water scarce conditions, it would be valuable to know what the actual soil moisture values are, in order to obtain a more relevant estimation of the irrigation requirements. It is therefore now possible for estimated available soil moisture values, obtained for different categories of the SPI, to be used in order to determine irrigation requirements for different severities of drought. This can be done for the specific months in which good correlations were obtained between the SPI and available soil moisture.

## NOMENCLATURE FOR CHAPTER 4

AVHRR: Advanced Very High Resolution Radiometry
CARIWIN: Caribbean Water Initiative
CDPMN: Caribbean Drought and Precipitation Monitoring Network
CIDA: Canadian International Development Agency
ENSO: El Niño/ Southern Oscillation
j: The value immediately before and after an event value at time t (in the deseasonalization process)
n: Number of years of data
NDVI: Normalized Difference Vegetation Index
NOAA: National Oceanic and Atmospheric Administration
NCDC: National Climatic Data Center
PDSI: Palmer's Drought Severity Index
SPI: Standardized Precipitation Index
$R^2$: Regression coefficient
TS : Sixteen-day mean in a time series
$TS_{sm}$: Seasonal value of the time series
$TS_{ds}$ is the sixteen day deseasonalized mean in the NDVI time series (or the monthly deseasonalized mean in the soil moisture time series),
U.S.: United States
USD: United States Dollar

# CHAPTER 4: The development of the Standardized Precipitation Index (SPI) and Normalized Difference Vegetation Index (NDVI)

Johanna Richards, Chandra A. Madramootoo, Adrian Trotman

**ABSTRACT**

Agricultural production is an important contributor to the Jamaican economy. However drought has the potential to cause millions of dollars in crop losses. There were crop losses amounting to six million USD in the 2000/2001 drought. Hence, drought index information is essential to the better planning for drought impacts and will allow for the introduction of mitigation measures by the agricultural sector. The objective of this chapter is therefore to describe the suitability of both the Standardized Precipitation Index (SPI), as well as the Normalized Difference Vegetation Index (NDVI), in reflecting water stressed conditions for three agricultural areas in Jamaica. The SPI was developed for different time scales, and then correlated to monthly soil moisture. Depending on location, either the one or three month SPI was found to be more representative of soil moisture conditions. The NDVI however, provides a suitable representation of the areas studied only for the driest months of the year, ranging from January to April depending on the location. This chapter provides soil moisture values for all the different categories/values of the SPI relating to water scarcity. It also provides irrigation requirements for the Moderately Dry and Severely Dry SPI drought categories.

**Keywords:** Standardized Precipitation Index, Normalized Difference Vegetative Index, Drought Management, Correlation Analysis, Regression Analysis

## 4.1 Introduction

Drought is a slowly developing phenomenon, and although several definitions formally exist, it is typically viewed as abnormally low water availability due to abnormally low levels of rainfall (Trotman et al., 2009). Drought in the West Indies is typically related to disruptions in the seasonal rainfall cycle, primarily caused by the El Niño / Southern Oscillation (ENSO) (Chen et al., 2005). Due to the long period of time over which drought spans, effective mitigation of the adverse effects can take place, provided that effective and timely monitoring of an impending drought is available (Cancelliere et al., 2007). There are several major challenges in dealing with drought. The first challenge is that drought is a creeping phenomenon, in that both its beginning and end are difficult to identify (Glantz, 1987). The reason for this is that neither the onset, nor the end of drought have a sharp distinction from non-drought periods (Glantz, 1987). Another challenge, particularly in developing countries, when dealing with drought is that generally no long term development policies are put into place for drought management (Glantz, 1987). Policy makers and government officials tend to view drought as a transient and unusual event; one which will not recur for a long time, and whose long term effects are downplayed by the return of the rain. Lastly, the impacts of drought on human activities can be subtle and pervasive (Glantz, 1987). There are indeed the obvious effects, such as withering of crops. However, there are also much more subtle and insidious effects, such as increased rural-to-urban migration rates and food prices.

During the period December 1996 to December 1998, Jamaica experienced below normal rainfall, causing significant losses in the agricultural sector. The Jamaican government had to respond to significant losses in the sugar sector by offering the sector a USD100 million assistance package in 1997 (Trotman et al., 2009). Subsequently, between October 1999 and March 2000, rainfall was less than 25% of normal in some places, resulting in crop losses of approximately six million USD (Trotman et al., 2009).

The SPI was developed by McKee et al. (1993) and since then has been applied extensively in many parts of the world including the United States (Hayes et al., 1999), Australia (Barros and Bowden, 2008), Europe (Cancelliere et al., 2007) and Africa (Ntale and Gan, 2003). It is the most internationally used drought indicator (Andreau et al., 2007). The index is computationally simple and is time-flexible, meaning that it can be developed over different time scales (Bonaccorso et al., 2003; Cancelliere et al., 2007; Guttman, 1998; Mendicino et al., 2008). This time flexibility gives the indices versatility, in that indices developed over short term time scales are applicable for monitoring short term meteorological drought. At the same time however, indices developed over long term time scales are applicable for the purposes of water resources management as well as the monitoring of long term (agricultural, hydrological and socio-economic) drought (Cacciamani et al., 2007; Guttman, 1998). These time scales in general range from three months to twenty-four months (Moreira et al., 2008).

The NDVI is an index that is used in order to measure and monitor plant growth and vegetation cover, and is derived from remote sensing measurements (USGS, 2010). The NDVI is calculated from the red and near-infrared reflectance from vegetation, which is measured by satellite. High correlations have been found between the NDVI and vegetation parameters such as green-leaf biomass, as well as green leaf area (Van De Griend and Owe, 1993). The NDVI values will increase with increasing vegetation cover and biomass, with bare soils having the lowest values (Van De Griend and Owe, 1993). The NDVI ranges from -1 to 1, with 0 and negative values represent non-vegetative surfaces, while values approaching 1 represent very dense vegetation (Anyamba et al., 2005).

The NDVI has also been found to be well-correlated to monthly mean soil moisture values in previous studies (Farrar et al., 1994). However, the NDVI was found to represent soil moisture better in dry years as opposed to wet years, due to a high soil moisture availability in wet years (Narasimhan et al., 2005). Narasimhan et al. (2005) also found that the NDVI provides a good representation of soil moisture, and can be used as a good agricultural drought indicator. Narasimhan et al. (2005) mentioned that the NDVI did not correlate well to soil moisture for brush species in rangeland and trees in forest land, however it responded well to changes in soil moisture for agricultural and pasture lands.

In general, in the West Indies, more complex and comprehensive indices such as the SPI, as well as the Palmer's Drought Severity Index (PDSI), are not used (Chen et al., 2005). The presence of drought, as well as mitigation strategies, are usually determined based on departures from the norm, such as the Percent Normal Index currently used in Jamaica (Meteorological Service of Jamaica, 2009). Currently, the Percent Normal of mean is the main index being used in order to make the public aware of the presence of drought conditions within Jamaica (Meteorological Service of Jamaica, 2009). There are five agricultural extension areas throughout the Island, and it is the responsibility of the agricultural extension office in the parish to collect the information required for rainfall indices (Chen et al., 2005). These indices include the number of rainfall days per month and the total rainfall received for the month. This data is compared to mean values in order to determine if a meteorological drought is occurring (Chen et al., 2005). Prediction indices are also developed for each region, based on crop type. These indices include hectares harvested during the month and to date, as well as hectares currently growing. These values are compared to mean values in order to determine anomalies in production levels (Chen et al., 2005). The Ministry of Agriculture uses the monthly rainfall and production indices in order to determine the early stages of an agricultural drought.

McGill University, in association with the Caribbean Institute of Meteorology and Hydrology, has developed the Caribbean Water Initiative (CARIWIN), which aims to promote integrated water resources management practices in the Caribbean region. CARIWIN is a six year project funded by the Canadian International Development Agency (CIDA). The development of drought indices and integrated water resources management tools have been identified by water resources managers and stakeholders as being an important step in the development of an integrated water resources management program, and is a high priority for research in the CARIWIN project (Trotman et al., 2008). The Caribbean Drought and Precipitation Monitoring Network (CDPMN) was proposed as a framework in which these indices could be developed. One focus of the CDPMN is to evaluate various drought indices such as the Standardized Precipitation Index (SPI) and Normalized Difference Vegetation Index (NDVI) for the Caribbean, and to relate these to hydrologic parameters such as soil miosture and streamflow.

## 4.2 Materials and methods

### 4.2.1 Study area description

The sites described previously in Chapter 3 were used for this study. These sites were selected because there is historical rainfall data spanning a minimum period of 30 years. Each site has distinctly different soil characteristics and farming practices. For the purposes of this research, the soil which dominated the 500 m radius of each climate station was used. The monthly available soil moisture was also calculated as described in Chapter 3.

### 4.2.2 Development of Normalized Difference Vegetation Index (NDVI)

The NDVI is calculated from the red and near-infrared reflectance from the vegetation, measured by satellite, and is calculated by the ratio (near-infrared - red)/(near-infrared + red) (Samson, 1993). The NDVI for Jamaica was obtained from the U.S. National Oceanic Atmospheric Administration (NOAA) Advanced Very High Radiometry Resolution (AVHRR) Landsat imagery, at a 250 m spatial resolution over 16 day composites. The NDVI has been shown to be a good indicator of vegetation health, due to that fact that chlorophyll absorbs broad-band red wavelengths and reflects near-infrared wave lengths (Rogers et al., 2009).

The NDVI values were obtained directly from the vector datasets produced by NOAA, and extracted over a 500 m radius from the rain gauge station, for the period 2000 to 2008. A 500 m radius was selected, as it was deemed to be a conservative approximation of the minimum area that would be affected by a rainfall event. The pixel values for the NDVI were then averaged over this 500 m radius for each 16 day composite and tabulated. Each of these 16 day composites underwent a time-weighted average smoothing procedure in order to obtain the NDVI for each month.

### 4.2.3 Seasonality analysis of the soil moisture and NDVI time Series

The distinct possibility exists that the seasonal component of a time series can lead to issues with covariance and autocorrelation within the time series, thus leading to inaccurate results with model development or regression analysis (Ji and Peters, 2003; Thompstone et al., 1985; Wang et al., 2007; Weissling and Xie, 2009). There are several ways in which this issue can be addressed. Ji et al. (2003) addressed the issue by using dummy variables to account for seasonality effects within their regression analysis. However, the issue of seasonality can also be addressed by removing the seasonal components from the time series. Therefore, the correlation and regression analysis was performed with the deseasonalized soil moisture, and deseasonalized NDVI time series. The deseasonalization process was carried out on the sixteen day composites of the NDVI before they were smoothed into one month composites, and on the monthly soil moisture.

The seasonal time series for the NDVI was first determined by calculating the average sixteen-day composite NDVI for each sixteen day period over the nine year time period. A three-point moving average was then taken for each sixteen day time period, in order to obtain a seasonal value for each sixteen day time period. This seasonal value was then subtracted from the value of each time period over the entire nine year time series, in order to determine the deseasonalized time series. The same procedure was used for the soil moisture, the difference being that each 'season' was the month. The process is described as follows, and was modified from Weissling and Xie (2009):

$$TS_{ds} = TS - TS_{sm} \qquad 4.1$$

$$TS_{sm} = \left(\sum_{j=t-1}^{t+1} \frac{\sum_{i=1}^{n} TS}{n}\right)/3 \qquad 4.2$$

Where $TS_{ds}$ is the sixteen day deseasonalized mean in the NDVI time series (or the monthly deseasonalized mean in the soil moisture time series), TS is the sixteen-day mean in a time series, $TS_{sm}$ is the three-point smoothed sixteen-day mean in a time series, j represents the value immediately before and after an event value at time t, and lastly n is the number of years for which the deseasonalized time series is computed. Ideally, long term means are considered appropriate for deseasonalizing time series (Wang et al., 2007; Weissling and Xie, 2009). However, this method has been applied successfully to much shorter NDVI time series than in this study (Weissling and Xie, 2009), and for that reason is considered appropriate for the nine-year NDVI time series in this study. Ideally, a longer time series would have been used as this would result in a more accurate representation of the NDVI, as it takes more years into account. However, the NDVI was only available for Jamaica as of 2001.

### 4.2.4 Standardized Precipitation Index

The Standardized Precipitation Index (SPI) is a meteorological index based solely on precipitation (McKee et al., 1993). The index is developed using monthly precipitation data which ideally is continuous over at least 30 years. The SPI can be developed over different time scales, such as 1, 3, 6, 12, 24 and 48 months. The precipitation data sets are then applied to a Gamma distribution function (McKee et al., 1993). This allows for the establishment of a relationship between probability and precipitation, leading to the calculation of a normally distributed probability density with a mean of zero and a standard deviation of unity (McKee et al., 1993). Thus negative values of the SPI represent drier conditions, while positive values represent wetter conditions.

For the purposes of this research, the SPI was obtained using a programming tool developed by the U.S. National Drought Mitigation Center (2006). The SPI was developed for the 3, 6, 9 and 12 month periods for the sites. The monthly rainfall data was obtained directly from the Meteorological Service of Jamaica from 1971-2008 for all three sites. In order to correlate the SPI to soil moisture, the one and three month SPI for each month was correlated to the concurrent monthly soil moisture. This was done over the entire 38 year time series. For example, the three month SPI for March 1971, was compared to the monthly soil moisture for March 1971. Like the NDVI, attempts were also made to lag the soil moisture by one and two months in order to see if the correlation results would improve.

### 4.2.5 Correlation and regression analysis

A bivariate correlation and regression analysis was carried out between monthly NDVI and soil moisture values. It was also carried out on the one and three month SPI values. A least squares regression analysis was carried out on the two analyses, with correlation coefficients reported within a 5% significance level. It was found through regression analyses that not all relationships were first order (linear). Figures B.4 to B.6 show the scatter plots and the lines of best fit. Cross-correlation (lag) analysis was carried out for the NDVI and soil moisture time series, by lagging the NDVI for a month and two months. It is important to understand that the NDVI was compared to soil moisture on a monthly basis, in other words, not as a continuous time series. This was done as the relationship between vegetation and soil moisture can change from month to month (Wang et al., 2007). The SPI and available soil moisture were also compared on a month-by-month basis, as the relationship between precipitation (and thus SPI) and soil moisture is different for each month. In general, in wetter months, small precipitation events can lead to the soil reaching field capacity. In drier months however, much larger precipitation events would be needed in order for the soil to reach field capacity.

The values of soil moisture were obtained using the regression coefficients obtained from the regression analyses. In order to determine the predicted value of the soil moisture from the regression model, the seasonal value needs to simply be added to this predicted deseasonalized value.

$$TS = TS_{ds} + TS_{sm} \tag{4.3}$$

These relationships were then used in order to determine soil moisture values for the different categories of the SPI, as used by the National Oceanic and Atmospheric Administration (NOAA) National Climatic Data Center (NCDC). These categories range from Severely Dry to Exceptionally Moist. In the body of the paper are soil moisture values relating to the categories Severely Dry to Near Normal. Included in Appendix B however (Tables B.1 to B.3) are soil moisture values from the Near Normal to Exceptionally Moist categories.

## 4.3 Results

### 4.3.1 The relationship between NDVI and soil moisture

As mentioned previously, the NDVI and soil moisture were compared on a month-by-month basis. As a result of the correlation analysis, it was found that the NDVI has a satisfactory ($R^2 \geq 0.7$) relationship with soil moisture in the months of January and March for Savanna-la-mar, January and April for Beckford Kraal, and lastly the months of January and February for Serge Island. The $R^2$ regression coefficients for each of these months are shown in Table 4.1. All values are reported within a 5% level of significance.

**Table 4.1: $R^2$ regression coefficients for NDVI and available soil moisture for relevant months**

| Location | Month | $R^2$ |
|---|---|---|
| **Savanna-la-Mar** | January | 0.73 |
| | March | 0.73 |
| **Beckford Kraal** | January | 0.75 |
| | April | 0.71 |
| **Serge Island** | January | 0.93 |
| | February | 0.74 |

### 4.3.2 The relationship between SPI and available soil moisture

The three month SPI showed reasonable $R^2$ regressions ($\geq 0.7$) for the months of February to June for Savanna-la mar, and the months of February to June, as well as

September for Beckford Kraal. However, the one month SPI had the best regression fits for Serge Island, but reasonable regression fits were only seen for the months of February, March and August (Table 4.2). All values are reported within a 5% level of significance. Table 4.2 shows the $R^2$ coefficients for each month. The coefficients for the three month SPI values and available soil moisture are reported for Savanna-la-mar and Beckford Kraal, unless otherwise indicated. The coefficients for the one month SPI and available soil moisture are shown for Serge Island.

**Table 4.2: $R^2$ regression coefficients for SPI and soil moisture**

| Month | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Savanna-la-Mar** | [1]0.6 | 0.7 | 0.8 | 0.7 | 0.8 | 0.7 | 0.6 | 0.5 | 0.4 | 0.4 | 0.4 | 0.5 |
| **Beckford Kraal** | [1]0.5 | 0.7 | 0.7 | 0.7 | 0.8 | 0.7 | 0.6 | 0.5 | 0.7 | 0.5 | 0.3 | 0.3 |
| **Serge Island** | 0.6 | 0.7 | 0.7 | 0.4 | 0.7* | 0.7* | 0.6 | 0.7 | 0.5 | 0.6 | 0.6 | 0.6 |

[1] $R^2$ regression coefficients for one month SPI relationships
*Auto-correlation found between the residuals in these months

Note that even though the months of May and June have $R^2$ coefficients of 0.7, they were not listed as months for which reasonable regression fits were obtained. The reason for this is that auto-correlation was found between the residuals for these months. It should also be noted that for both Savanna-la-Mar and Beckford Kraal, the $R^2$ coefficients were higher for the one month SPI for the month of January than the three month SPI, and so these are the ones listed in the table. The correlations shown in Table 4.2 highlight the months for which relationships between the SPI and available soil moisture can be derived through use of a curve of best fit.

## 4.4 Discussion

### 4.4.1 NDVI and available soil moisture

The NDVI only had reasonable correlations for months during the driest period of the year (January and March for Savanna-la-Mar, January and April for Beckford Kraal and January and February for Serge Island). Due to the limited months of good regressions between the NDVI and soil moisture, it is not recommended for use at these sites. Soil and vegetation types play a significant role in the ability of the NDVI to represent soil moisture.

While none of these sites could be classified as arid or semi-arid, the fact that the dry months are the only times during which relationships between the NDVI and available soil moisture exist suggests that the vegetation response to soil moisture is far stronger during drier than wetter periods. Narasimhan et al. (2005) stated that the study site within the high rainfall zone of their study area had low correlations between NDVI and soil moisture, as the NDVI did not fluctuate much with changes to soil moisture, as a result of the high annual rainfall. There are three main factors which could have influenced the results: soil type, aridity and vegetation.

Effect of soil types on relationship between NDVI and available soil moisture

Soil types in this study might have affected the relationship of the NDVI correlations to soil moisture. As clay soils tend to retain water for much longer periods than sandy soils (due to poor drainage and higher available water capacity in clay soils), changes in precipitation might not be reflected in the vegetation as readily as it would in a sandy soil. This is supported by Farrar et al. (1994), who reported that in their study, the soil moisture was higher in the cambisols and vertisols (soils with the highest clay content), than in the arenosols (soils with the highest sand content). Note that the highest $R^2$ regression coefficient was 0.93, and was achieved for January in Serge Island. It is possible that the soil type might have been responsible for this. Serge Island has a sandy loam, which has the smallest available water capacity of all the soils.

Effect of aridity on relationship between NDVI and available soil moisture

Due to the high annual rainfall that each of the sites receive, the reasonable correlations were only seen for the driest months of the year for the study locations, and this supports the idea that the NDVI is really only a robust estimator of soil moisture in arid or semi-arid areas.

The study performed by Narasimhan et al. (2005), was located in Texas. However their study locations spanned a large range of precipitation regimes. This study also determined that the NDVI was correlated to the surface soil moisture of the concurrent month of the growing season, but found this correlation to be stronger during dry years. Farrar et al. (1994) investigated the relationship between NDVI and soil moisture in semi-arid Botswana, and this study also determined that the NDVI was correlated to the surface soil moisture of the concurrent month of the growing season. Wang et al. (2007) stated that in semi-arid environments, NDVI changes closely with soil moisture as soil moisture is the major controlling factor for vegetation. In these arid and semi-arid environments, root-zone soil moisture controls surface vegetation health and coverage (Wang et al., 2007). This is because water is one of the main controlling factors for vegetation growth. Therefore, soil moisture deviation from the norm causes a change in vegetation characteristics. As the NDVI is derived from remote sensing measurements based on the spectral signature of vegetation in near infrared and red bands, there is a strong association between the NDVI and vegetation cover, and by extension, soil moisture in the root zone (Wang et al., 2007). Lastly, Wang et al. (2007) showed that the NDVI at humid sites takes longer to respond (10 days) to soil moisture than at arid sites (5 days).

Effect of vegetation type on relationship between NDVI and available soil moisture

Narasimhan et al. (2005) also mentioned that the NDVI did not correlate well to soil moisture for brush species in rangeland and trees in forest land, very possibly due to deeper rooting systems. Much stronger correlations were seen with agricultural lands and pasturelands however, as they have root systems that can only extract water from shallower depths, and so this type of vegetation responds quickly to changes in soil moisture. In Jamaica, typical farms are small scale (between 1 to 2 ha) (STATIN, 2007). In addition, these farms are usually interspersed with natural vegetation. As a result, it was not possible at any of the three study areas to differentiate between locations that were solely agricultural and locations that were only brush-land or woodland. This also explains the generally poor correlations between NDVI and available soil moisture for the sites.

### 4.4.2 SPI and available soil moisture

As shown in Table 4.2, the SPI only had good correlations to available soil moisture in particular months. A possible reason is that in dry months, the changes in precipitation would be better reflected in soil moisture. May, despite being considered a wet month, had good correlations for both Savanna-la-mar and Beckford Kraal. This might be due to the fact that it immediately follows the driest months of the year, and so the soil would likely not be at field capacity, and would therefore still respond to increases in precipitation. Therefore, during May, the increase in rainfall is accompanied by increasing soil moisture, resulting in good correlations.

Tables 4.3 to 4.5 show actual values of soil moisture based on the categories of the SPI used by the NOAA NCDC, for each location, and for each relevant month, for negative values of the SPI. These categories that represent water scarcity have been defined by NOAA NCDC as Near Normal, Abnormally Dry, Moderately Dry, Severely Dry, Extremely Dry and Exceptionally Dry. Each of these categories is defined by a range in SPI values. For example, the Near Normal category is defined by a range in SPI values of -0.5 to 0.5, while the Abnormally Dry category is defined by a range of -0.79 to -0.51. As these are the predefined categories and definitions used in the U.S., these same categories will be applied here within this research.

The values are bounded at the lower limit at 0 mm, and bounded at the upper limit at the available water capacity of the soil. The curves cannot represent these boundary conditions, and so the values had to be forcibly bounded at the lower and upper limits of the soil moisture. For each category of water scarcity (such as Near Normal), the plant available water is shown for the lower and upper limit of that category. Therefore, in Table 4.3, 0.5 represents the upper limit of the Near Normal category, and the plant available water is shown for this SPI value, as well as the lower limit of that category.

**Table 4.3: Plant available soil moisture values for the SPI categories for Savanna-la-Mar (mm)**

| Water Availability | 3 month SPI values | Feb | Mar | Apr | May | Jun |
|---|---|---|---|---|---|---|
| Near normal | 0.5 | 70 | 47 | 56 | 121 | 122 |
| | -0.5 | 33 | 11 | 15 | 58 | 66 |
| Abnormally dry | -0.51 | 32 | 11 | 15 | 58 | 65 |
| | -0.79 | 22 | 5 | 6 | 40 | 50 |
| Moderately dry | -0.8 | 22 | 4 | 6 | 40 | 49 |
| | -1.29 | 3 | 0 | 0 | 9 | 21 |
| Severely dry | -1.3 | 3 | 0 | 0 | 0.8 | 21 |
| | -1.59 | 0 | 0 | 0 | 0 | 4 |
| Extremely dry | -1.6 | 0 | 0 | 0 | 0 | 4 |
| | -1.99 | 0 | 0 | 0 | 0 | 0 |
| Exceptionally dry | -2 | 0 | 0 | 0 | 0 | 0 |

**Table 4.4: Plant available soil moisture values for the SPI categories for Beckford Kraal (mm)**

| Water Availability | 3 month SPI Value | Feb | Mar | Apr | May | Jun | Sep |
|---|---|---|---|---|---|---|---|
| Near normal | 0.5 | 129 | 118 | 117 | 173 | 149 | 165 |
| | -0.5 | 77 | 61 | 60 | 97 | 84 | 90 |
| Abnormally dry | -0.51 | 76 | 61 | 60 | 96 | 84 | 89 |
| | -0.79 | 62 | 45 | 44 | 75 | 66 | 68 |
| Moderately dry | -0.8 | 61 | 44 | 43 | 74 | 65 | 67 |
| | -1.29 | 36 | 16 | 16 | 37 | 33 | 31 |
| Severely dry | -1.3 | 35 | 16 | 15 | 36 | 33 | 30 |
| | -1.59 | 20 | 0 | 0 | 14 | 14 | 8 |
| Extremely dry | -1.6 | 20 | 0 | 0 | 14 | 13 | 07 |
| | -1.99 | 0 | 0 | 0 | 0 | 0 | 0 |
| Exceptionally dry | -2 | 0 | 0 | 0 | 0 | 0 | 0 |

**Table 4.5: Plant available soil moisture values for the SPI categories for Serge Island (mm)**

| Water Availability | 1 month SPI Value | Feb | Mar | Aug |
|---|---|---|---|---|
| Near normal | 0.5 | 38 | 25 | 88 |
| | -0.5 | 12 | 3 | 45 |
| Abnormally dry | -0.51 | 11 | 3 | 44 |
| | -0.79 | 6 | 0 | 32 |
| Moderately dry | -0.8 | 6 | 0 | 31 |
| | -1.29 | 0 | 0 | 8 |
| Severely dry | -1.3 | 0 | 0 | 8 |
| | -1.59 | 0 | 0 | 0 |
| Extremely dry | -1.6 | 0 | 0 | 0 |
| | -1.99 | 0 | 0 | 0 |
| Exceptionally dry | -2 | 0 | 0 | 0 |

Tables 4.3 to 4.5 show the values of available soil moisture for different values of the SPI. Theoretically, based on the assumptions of the model (Equations 3.1 and 3.2, Chapter 3), a soil available water content of zero is never actually reached, as the amount of water withdrawn from the soil is proportional to the amount of water available in the soil. As a result, the available soil moisture values theoretically approach zero, without actually reaching it. However, the regression curves could not capture this boundary, and as a result the regression equations give 'negative' available soil moisture values for the lowest values of the SPI (refer to Figures B.4 to B.6 to see the regression curves). Whenever 'negative' soil moisture values were achieved from the regression curves, the numbers were forcibly bounded by assuming an available water capacity of zero.

Note that for both Savanna-la-mar and Beckford Kraal, a soil available water content of zero occurs the earliest during March and April, meaning that it occurs at the lower boundary of moderately dry/upper boundary of severely dry category, with corresponding SPI values of -1.29/-1.30 respectively. This supports the fact that these are the driest months (refer to Figures B.1 to B.3 for monthly average rainfall for each three locations). Interestingly, for Savanna-la-mar, it occurs the latest, at the month of June (the lower boundary of the extremely dry category with corresponding SPI value of -1.99), suggesting that soil moisture during this month exceeds that of May. For Beckford Kraal, a soil available water content of zero occurs at the same point (the lower boundary of the extremely dry category) in May. However, there is very little difference between the soil moisture values at the upper end of this category (SPI value of -1.60), with a 10 mm difference between May and June. For Serge Island, the wettest month represented in the Table 4.5 is August, with March again being the driest month. A soil available water content of zero occurs at the upper end of the moderately dry category in March, and at the lower bound of the severely dry category in August. Note that a soil available water content of zero occurs at less severe water scarce conditions in March for Serge Island, than for either Savanna-la-mar or Beckford Kraal. It is likely that soil type is the main reason for this. The influence of soil type on the relationship between the SPI values and available soil moisture is discussed in the following section.

Effect of soil type on relationship between SPI and available soil moisture

As mentioned previously, the dominant soil type at Serge Island was a sandy loam, which has the most limited water holding capacity of all the soils in this study. As a result, the soil moisture in any particular month would have a much smaller dependence on soil moisture in the previous months (compared to a clay soil for instance), due to this quick response. Likewise, the one month SPI does not take into account rainfall in previous months. However, the loam and clay soils show a slower response to rainfall, due to the fact that they have much larger water capacities. The soil moisture conditions in a particular month would be far more dependent on soil moisture conditions in a previous month. Likewise, the three month SPI for a particular month takes into account the two previous months of rainfall. It is therefore reasonable to state, that depending on the type of soil, either the one or three month SPI may be more useful in monitoring agricultural drought. In light of this, it is understandable why the one month SPI had the best correlations for Serge Island, while the three month SPI had the best correlations for Savanna-la-mar and Beckford Kraal.

Sims et al. (2002) performed a study in North Carolina to investigate the potential of the SPI for representing short-term precipitation and soil moisture variation. The authors suggested that changes in soil types could play a significant role in the relationship between SPI and soil moisture. They suggested that SPI time series which have been averaged over longer time periods would have better correlations with soil moisture in deeper soil layers.

<u>Effect of SPI averaging time period on relationship between SPI and available soil moisture</u>

Ji and Peters (2003) also found that the three month SPI is best for representing the effects of drought severity on vegetation cover. The authors suggest that this is due to the fact that the impact of water deficits on vegetation is cumulative, meaning that vegetation does not respond instantaneously to precipitation. As a result there is a time lag in the vegetation response to precipitation. This time lag is captured by the smoothing action of the three month SPI, which captures precipitation behavior over the particular month in question, as well as the two previous months. The study conducted by Sims et al. (2002) also showed that the short-term (one to three month) SPIs yielded the highest correlation between SPI and soil moisture. Serge Island had the best correlations for the one month SPI. As mentioned in the previous sub-section, this is most likely due to soil type.

<u>Applicability of results to determining irrigation requirements</u>

The SPI values can be used to determine monthly soil moisture values during water scarce conditions. The information provided in Tables 4.3 to 4.5 can be used based on the drought condition which is being experienced. These soil moisture values can then be used in order to determine irrigation requirements during water scarce conditions. In general, irrigation is only required during the drier months of the year. There are limitations concerning the fact that there are no good correlations for the wetter months of the year. If there is indeed water scarcity during these months, then this tool would not be applicable. However, it at least provides a means of determining the irrigation requirements during the months of the year in which the highest irrigation dependency exists.

Irrigation requirements for the lower bounds of the moderately dry and severely dry SPI categories have been calculated for the three sites, and are shown in Tables 4.6 to 4.8 below. The information in these tables is meant to be used for planning purposes. Note that for both Savanna-la-mar and Serge Island, available soil water values of 0 mm are experienced during the Moderately Dry periods for March and April, and February and March respectively. As a result, the irrigation requirements for these months are the same, regardless of the drought intensity.

**Table 4.6: Irrigation requirements for the Moderately and Severely Dry categories of drought for Savanna-la-mar**

| SPI Drought category | Crop | Irrigation requirement at end of month (mm) | | | | |
|---|---|---|---|---|---|---|
| | | February | March | April | May | June |
| Moderately Dry | Vegetables | 121 | 140 | 122 | 11 | 52 |
| | Sugarcane | 68 | 37 | 19 | 39 | 41 |
| Severely Dry | Vegetables | 121 | 140 | 122 | 11 | 52 |
| | Sugarcane | 85 | 48 | 33 | 81 | 74 |

**Table 4.7: Irrigation requirements for the Moderately and Severely Dry categories of drought for Beckford Kraal**

| SPI Drought category | Crop | Irrigation requirement at end of month (mm) | | | | | |
|---|---|---|---|---|---|---|---|
| | | February | March | April | May | June | September |
| Moderately Dry | Vegetables | 70 | 91 | 97 | 10 | 93 | 0 |
| | Sugarcane | 0 | 0 | 0 | 9 | 10 | 9 |
| Severely Dry | Vegetables | 86 | 107 | 113 | 26 | 109 | 0 |
| | Sugarcane | 0 | 10 | 15 | 32 | 29 | 32 |

**Table 4.8: Irrigation requirements for the Moderately and Severely Dry categories of drought for Serge Island**

| SPI Drought category | Crop | Irrigation requirement at end of month (mm) | | |
|---|---|---|---|---|
| | | February | March | August |
| Moderately Dry | Vegetables | 119 | 148 | 100 |
| | Sugarcane | 94 | 121 | 108 |
| Severely Dry | Vegetables | 119 | 148 | 100 |
| | Sugarcane | 94 | 121 | 116 |

In order to facilitate the determination of irrigation requirements for different severities of drought, all the relevant parameters have been calculated as described in Chapter 3, and are provided in Appendix A. Effective precipitation values for cumulative probabilities ranging from 1% to 99% for all the sites are shown in Tables A.1 to A.3. Monthly crop evapotranspiration values are shown in Table A.4, and average monthly available soil moisture values are presented in Table A.5. The available soil moisture values for different drought severities have been presented in Tables 4.3 to 4.5. Therefore, an innovative tool now exists for determining irrigation requirements during water scarce conditions.

The results as they now stand are very location specific. However, until further research takes place, then these results can be used as a guideline for irrigation planning in other areas of the relevant parishes In order for this to take place however, more climatic stations need to achieve historic rainfall records of 30 years or more, as the lack of suitable rainfall data was one of the biggest limiting factors in this study.

## 4.5 Conclusions

The applicability of both the NDVI and SPI for representing soil moisture conditions at three sites in Jamaica was evaluated. The NDVI was found to have the best correlations during the driest months of the year for all three locations. In other studies, the NDVI was found to represent soil moisture better in dry years as opposed to wet years, due to a high soil moisture availability during wet years (Narasimhan et al., 2005). The results from this study support this conclusion, in that the only months for which the NDVI provided a suitable representation of soil moisture were the driest months of the year for all three locations. Due to the limited months for which good correlations were seen between the NDVI and soil moisture, it is not recommended for use at these sites. Soil and vegetation types play a significant role in the ability of the NDVI to represent soil moisture, and future studies involving other types of vegetation and soil might result in much better correlations.

Either the three month or one month SPI was found to have reasonable $R^2$ correlations for particular months of the year in all three study areas. The three month SPI is preferred for use at the Savanna-la-mar and Beckford Kraal sites when planning for agricultural drought. However, the one month SPI is preferred for the Serge Island site. For the Savanna-la-Mar and Beckford Kraal locations, the months of March to June had the best correlations, while for the Serge Island site, the months of February, March and August had the best correlations. A limitation to the applicability of these results to planning is the fact that the SPI was only correlated to soil moisture determined for particular soils.

The issue of agricultural development is a complex one in the Jamaican context, and the provision of irrigation data is but one small step in increasing the viability of Jamaican farmers. Among the myriad of socio-economic and political factors, it is becoming increasingly important that a comprehensive approach be taken to improve agricultural production within the island. The coupling of drought indices and irrigation demands is an attempt to do just that, and to further this end, irrigation demands were determined for the Moderately Dry and Severely Dry SPI categories for both vegetables and sugarcane.

The results from this study can be used, in conjunction with results from Chapter 3, for determining monthly irrigation requirements for certain months of the year, for different intensities of drought, as all the information that is necessary for these calculations have been published within this manuscript.

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## CONNECTING TEXT TO CHAPTER 5

The manuscript is co-authored by my supervisor Dr. Chandra Madramootoo. All literature cited in this chapter are listed in the reference sections at the end of this chapter, as well as at the end of this thesis. Chapters 3 and 4 provided the tools with which to determine irrigation demands for both sugarcane and vegetables during different severities of drought. However, the question arises as to how to properly plan to supply this water, and how to understand the different components of the water balance in a way which allows for proper withdrawals of water from surface water or groundwater systems. The Soil and Water Assessment Tool (SWAT) is a hydrologic model which provides a powerful tool for planning within agricultural watersheds, and can be used in order to provide this information. Hence, it can be used as a planning tool for determining the effects of irrigation withdrawals on surface or groundwater systems.

However, the study sites are in three different watersheds, which are all in different parts of the island. Due to time and data availability limitations, it was not possible to build SWAT for the respective watersheds of all the study areas. Therefore, the SWAT model was built in the Rio Nuevo watershed, in the parish of St. Mary. This watershed was chosen as it is the location of the CARIWIN pilot site, and it is a rural watershed which is underdeveloped in terms of irrigation systems.

Despite the disparity in study site locations, the development of SWAT for this watershed is meant to provide the foundation for its development in other watersheds in the Island, leading to improved water scarcity management.

## NOMENCLATURE FOR CHAPTER 5

ΔSW: The change in soil moisture depth (predicted by SWAT)
$\infty$: Infinity
ALPHA_BF: Baseflow Alpha Factor
ANSWERS: Areal Non-point Source Watershed Environment Response Simulation
BANA: Bananas land use in SWAT
BBDB: Bamboo and Broadleaf landuse in SWAT
BBFD: Bamboo and Fields landuse in SWAT
CABG: Cabbages landuse in SWAT
CARIWIN: Caribbean Institute of Meteorology and Hydrology
CN: Curve Number
DBFD: Disturbed Broadleaf and Fields landuse in SWAT
DEM: Digital Elevation Model
DSBL: Disturbed Broadleaf landuse in SWAT
ESCO: Soil Evaporation Compensation Factor
ET: Evapotranspiration (predicted by SWAT)
FIDS: Fields landuse in SWAT
GIS: Geographic Information Systems
GW_DELAY: Groundwater delay time
GWQMN: Threshold depth of shallow water in the aquifer required for return flow to occur
GW_REVAP: Groundwater 'revap' coefficient
HTPR: Hot peppers landuse in SWAT
HRU: Hydrologic Response Unit
LATQ : Lateral shallow sub-surface flow to the reach (predicted by SWAT)
NSE: Nash Sutcliffe Efficiency coefficient
OAT: One-at-a-time
PBIAS: Percent Bias coefficient
PCP: Precipitation (as input into SWAT)
PERC: Deep water percolation
RCHDP: Deep Aquifer Percolation Fraction
REVAPMN: Threshold depth the shallow aquifer required for deep percolation to occur
RSR: Ratio of the root mean square error to the standard deviation of measure data (RSR)
SWAT: Soil and Water Assessment Tool
SCS: Soil Conservation Service
SURQ is the surface runoff (predicted by SWAT)
TOMA: Tomatoes landuse in SWAT
U.S.: United States
WA: Wavelet Analysis

# CHAPTER 5: Using SWAT to simulate hydrologic conditions in Jamaica

Johanna Richards, Chandra A. Madramootoo

**ABSTRACT**

The Soil and Water Assessment Tool (SWAT) was used in order to simulate the hydrologic characteristics of the Rio-Nuevo sub-basin, located in the parish of St. Mary. Historical climatic data (precipitation and temperature) was obtained for the watershed, while streamflow data was obtained for the Rio Nuevo, which drains the watershed. The model was calibrated over the period 2002-2004, and validated from the period 2005-2007. Nash-Sutcliffe Efficiency (NSE) coefficients of performance of 0.76 and 0.50 were obtained for calibration and validation respectively for streamflow. In addition, SWAT was used in order to assess streamflow availability for irrigation supply during dry periods, and the results show that in drought periods, the stream cannot supply the necessary water needed to the agricultural areas. This paper outlines the development of SWAT for the Rio Nuevo watershed, and describes the potential for use in agricultural water scarcity management.

**Keywords**: Hydrology, Streamflow, Basin-scale Modelling, SWAT, Distributed Modelling, Calibration, Validation, Irrigation Planning

## 5.1 Introduction

Jamaica's water resources are under increasing risk of degradation and depletion, especially in light of increasing population growth and urbanization (Ricketts, 2005). As a result, the use of hydrologic models in the island is an increasingly important tool for agricultural water planning, as distributed parameter models such as SWAT are key to basin-level assessment of water resources availability (Jayakrishnan et al., 2005). Chapter 3 provided typical monthly irrigation demands for sugarcane and vegetables, while also providing irrigation demands for certain water stressed conditions. Chapter 4 provided tools which will enable planners to understand the relationship between SPI values and available soil moisture. However, these tools are mostly reactive, in the sense that they outline methods to respond to water scarcity. Therefore, a pro-active approach to agricultural water scarcity management needs to take place through planning. The understanding of which cropping methods can be used in order to save water etc., can lead to decreased demands on water, thus lessening the stress on water resources during water scarce conditions.

SWAT is a continuous, long-term, physically based, semi-distributed hydrologic model, developed by the U.S. Department of Agriculture (Neitsch et al., 2005; Zhang et al., 2008). It is an effective planning tool, in that it can be used in order to gain an improved understanding of the water balance, while at the same time determining water savings from different management scenarios (Immerzeel et al., 2008; Santhi et al., 2005). It was specifically with this issue in mind that the SWAT model was built for the Rio Nuevo watershed, which is the location of the Caribbean Water Initiative (CARIWIN) Jamaican pilot site. At the time of this research, the only previously published work which the authors were able to find which described the use of SWAT in Jamaica was by Evelyn (2007), in which SWAT was used to determine optimum forest cover for minimizing run-off in a degraded watershed. This was done without any calibration or validation of the model.

SWAT is a conceptual model that works on daily time steps (Arnold and Fohrer, 2005). SWAT can simulate surface and sub-surface flow, soil erosion, nutrient data analysis and sediment deposition, and has been applied worldwide for hydrologic and water quality simulation (Zhang et al., 2008). SWAT has also been applied extensively over a wide range of spatial scales. Gollamudi (2007) applied SWAT to two fields in Southern Quebec, while Zhang et al. (2007), applied SWAT to the 5239 $km^2$ watershed in China for the simulation of daily and monthly stream flows.

SWAT was initially developed to predict the impact of land management practices on water, agricultural chemical yields and sediment in large, complex watersheds (Neitsch et al., 2005). It consequently requires a large amount of specific information such as land use, climatic information and soil types. This input data is then used to directly model physical processes such as sediment movement and nutrient cycling (Neitsch et al., 2005). SWAT has been integrated with Geographical Information Systems (GIS) (ArcSWAT 2005), simplifying the process of integrating spatially variable datasets into the model. In addition to this, multiple simulations can be carried out using SWAT due to its high computational efficiency (Arnold and Fohrer, 2005). This is particularly useful in light of the fact that the Rio Nuevo basin consists of a mosaic of agricultural plots, natural woodland, and urban settlements. For this reason, SWAT was particularly desirable as it allows for the easy input of spatially variable landuse and soil data.

There are several hydrologic models which could also have been potentially used in this study, such as ANSWERS-2000 (Bouraoui and Dillaha, 2000) or AGNPS (Young and Onstad, 1990). However, SWAT is a model available to the public domain, and one which has been used extensively in many countries worldwide, including developing countries (Zhang et al., 2008). Due to limited resources, it is important that any model used in Jamaica be as robust as possible, while at the same time cost effective. A few of the many advantages of SWAT are that it is computationally efficient, uses readily available inputs, and enables users to study long term impacts (Neitsch et al., 2005). In addition, SWAT can be used in the future for modelling water quality and sediment characteristics, as well as streamflow.

SWAT is described as a semi-distributed model as Hydrologic Response Units (HRUs) are used for the organization of simulations and outputs (Salerno and Tartari, 2009). These HRUs represent areas of homogeneous management, land use, and soil type characteristics. Run-off is calculated for each HRU, and then combined at the sub-basin level. This run-off is then routed in order to account for total run-off (Salerno and Tartari, 2009). Three methods of calculating evapotranspiration have been incorporated into SWAT: (i) the Penman-Monteith method (Allen, 1986; Allen et al., 1989; Monteith, 1965), (ii) the Preistley-Taylor method (Preistley and Taylor, 1972) and (iii) the Hargreaves Method (Hargreaves and Samani, 1985). The relevance of each method to the model depends not only on the types of inputs available, but also on the climatic conditions of the geographic area in question.

The main objectives of this study were to (i) apply the SWAT model to the Rio Nuevo sub-basin, (ii) calibrate and validate the model to streamflow, using 6 years of measured data, and lastly (iii) assess the feasibility of the model for agricultural water scarcity planning in Jamaica.

## 5.2 Materials and methods

### 5.2.1 Site description

The Rio Nuevo sub-basin is a 110 $km^2$ sub-basin, located in the Blue Mountain North watershed, which ranges from the Blue Mountains to the northern shore of the island. Figure 5.1 shows the watershed location. The Rio Nuevo flows northward towards the coast and originates in the Blue Mountains, a mountainous ridge that runs throughout the island.

The Rio Nuevo watershed is located in the parish of St. Mary, which is in the north-eastern section of the island. St. Mary’s largest industry is agriculture, with crops such as bananas, citrus, coconuts, coffee and sugar cane being produced (St. Mary Parish Library, n.d.). St. Mary was formerly a leading contributor to the Jamaican economy through agricultural production. However, it has suffered significant economic decline over the past two decades. This is mainly due to the collapse of the coconut and sugar industries, which were the main agricultural mainstays of the parish (St. Mary Partnership, 2006). Despite the decline which has occurred in the agricultural sector in St. Mary, agriculture and agro-processing are still regarded as the main factors in St.

Mary's journey to economic recovery (St. Mary Partnership, 2006). Consequently, diversity in agricultural production, both on a small and a large scale, is being heavily encouraged by the St. Mary Parish Council.

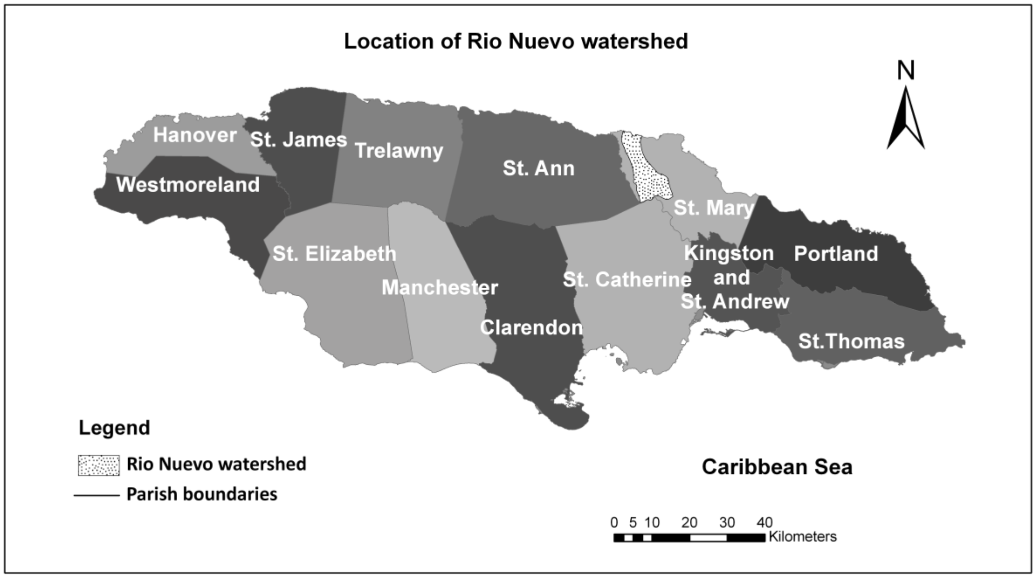


**Figure 5.1: Location of Rio Nuevo watershed**

The watershed is rural, with agriculture and woodland occupying most of the basin. Crops grown in this area include bananas (*Musa sapientum*), plantains (*Musa paradisiaca*), papayas (*Carica papaya*), scotch bonnet peppers (*Capsicum chinense*), cabbages (*Brassica oleracea capitata*), tomatoes (*Lycopersicon esculentum*) and pak choy (*Brassica rapa var. chinensis*) (Edwards, 2009 , *personal communication*). Land use throughout the watershed consists mostly of agricultural lands, as well as forested or woodland areas. The land use distribution is described in Table 5.1. Small farmers dominate the agrarian landscape in Jamaica, and are defined as those with farms of size 2 ha or less (FAO, 2003). There is therefore a mosaic of woodland and small farms throughout the watershed. Landuse descriptions are shown in Table 5.2. These descriptions were obtained from Evelyn (2007), and were developed by the Jamaican Department of Forestry. SWAT requires four letter acronyms to represent each landuse, and these are shown for each landuse under the heading "SWAT definition" in Table 5.2. Lastly, the area is dominated by soils high in clay content, the distribution of which is shown in Table 5.3. The hydrologic soil groups shown in the tables represent the infiltration capacity and drainage characteristics of the soils, with group A having the highest infiltration and drainage capacities, and group D having the lowest.

**Table 5.1: Watershed distribution of land uses as represented in SWAT**

| Landuse | % Watershed Cover |
|---|---|
| Disturbed Broadleaf | 39.19 |
| Fields and Disturbed Broadleaf | 33.53 |
| Fields | 17.2 |
| Disturbed Broadleaf and Fields | 6.74 |
| Bamboo and Disturbed Broadleaf | 1.28 |
| Bamboo and Fields | 1.01 |
| Plantation (Redefined as agricultural row crops) | 0.69 |
| Built up | 0.36 |

**Table 5.2: Reclassification of land uses in SWAT (adapted from Evelyn, 2007)**

| Original Landuse | Definition of land use | SWAT definition |
|---|---|---|
| Disturbed Broadleaf | Disturbed broadleaf forest with broadleaf trees at least 5 m tall and species indicators of disturbance such as Cecropia peltata (trumpet tree) | DSBL |
| Built-up | Urban areas, including low to high density | Residential-Medium/low density (URML) |
| Fields | Herbaceous crops, fallow cultivated grass/ legumes | FIDS |
| Bamboo and broadleaf | > 50% bamboo, > 25% disturbed broadleaf forest | BBDB |
| Bamboo and fields | >50% bamboo, >25% fields | BBFD |
| Disturbed Broadleaf and fields | > 50% disturbed broadleaf forest, >25 % fields | DBFD |
| Plantation | Tree crops, shrub crops like sugar cane, bananas, citrus and coconuts | Cabbages (CABG)<br>Tomatoes (TOMA)<br>Hot peppers (HTPR)<br>Bananas (BANA) |
| Fields and disturbed broadleaf | >50 % fields; >25% disturbed forest | FDDB |

**Table 5.3: Soil type distribution for the Rio Nuevo watershed**

| Soil | % Watershed Area | % Clay | % Silt | % Sand | Hydrologic Group |
|---|---|---|---|---|---|
| **Killancholly** | 33.89 | 60 | 20 | 20 | B |
| **Carron** | 22.67 | 48 | 34 | 18 | B |
| **Donnington** | 15.67 | 29 | 45 | 26 | A |
| **Bonnygate** | 12.48 | 55 | 29 | 16 | A |
| **Union** | 9.73 | 53 | 38 | 9 | C |
| **Waitabit** | 3.59 | 58 | 17 | 25 | B |
| **Belfield** | 1.18 | 22.5 | 52.7 | 24.8 | C |
| **St. Ann** | 0.5 | 45 | 54 | 1 | A |
| **Bundo** | 0.28 | 60 | 20 | 20 | B |

Elevation in the watershed ranges from 3 m above sea level near the coast to 591 m above sea level in the Blue Mountain range (Figure 5.2). The legend in Figure 5.2 shows the elevation as divided into natural (Jenks) categories. Approximately 85% of the watershed consists of aquiclude rock material, thus resulting in low potential for interaction between surface, or soil moisture and groundwater throughout the majority of the watershed. The remaining 15% is limestone (karstic) aquifer. A hydrostratigraphic map is shown in Figure 5.3.

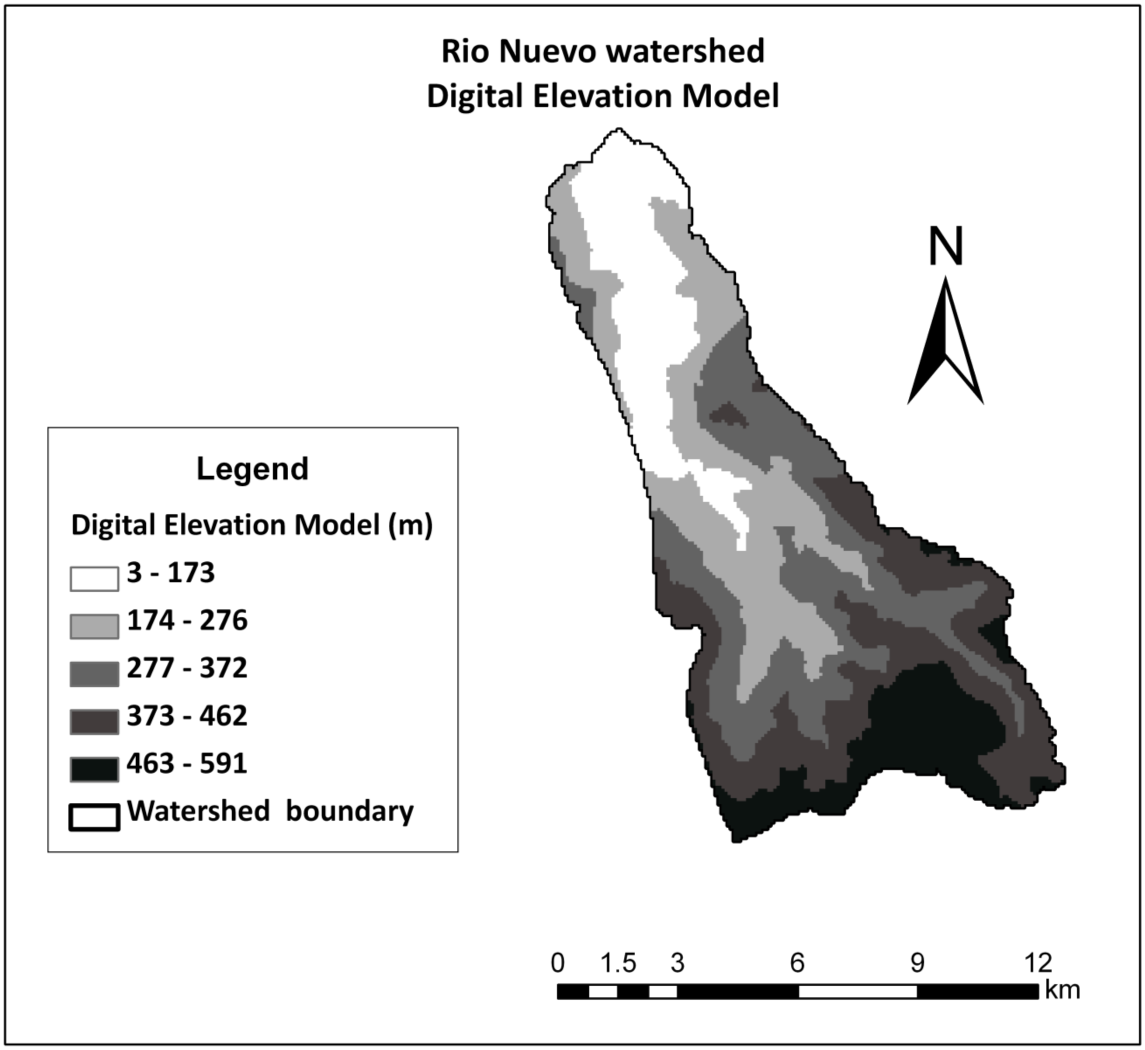


**Figure 5.2: Digital Elevation Model (DEM) of Rio Nuevo watershed**

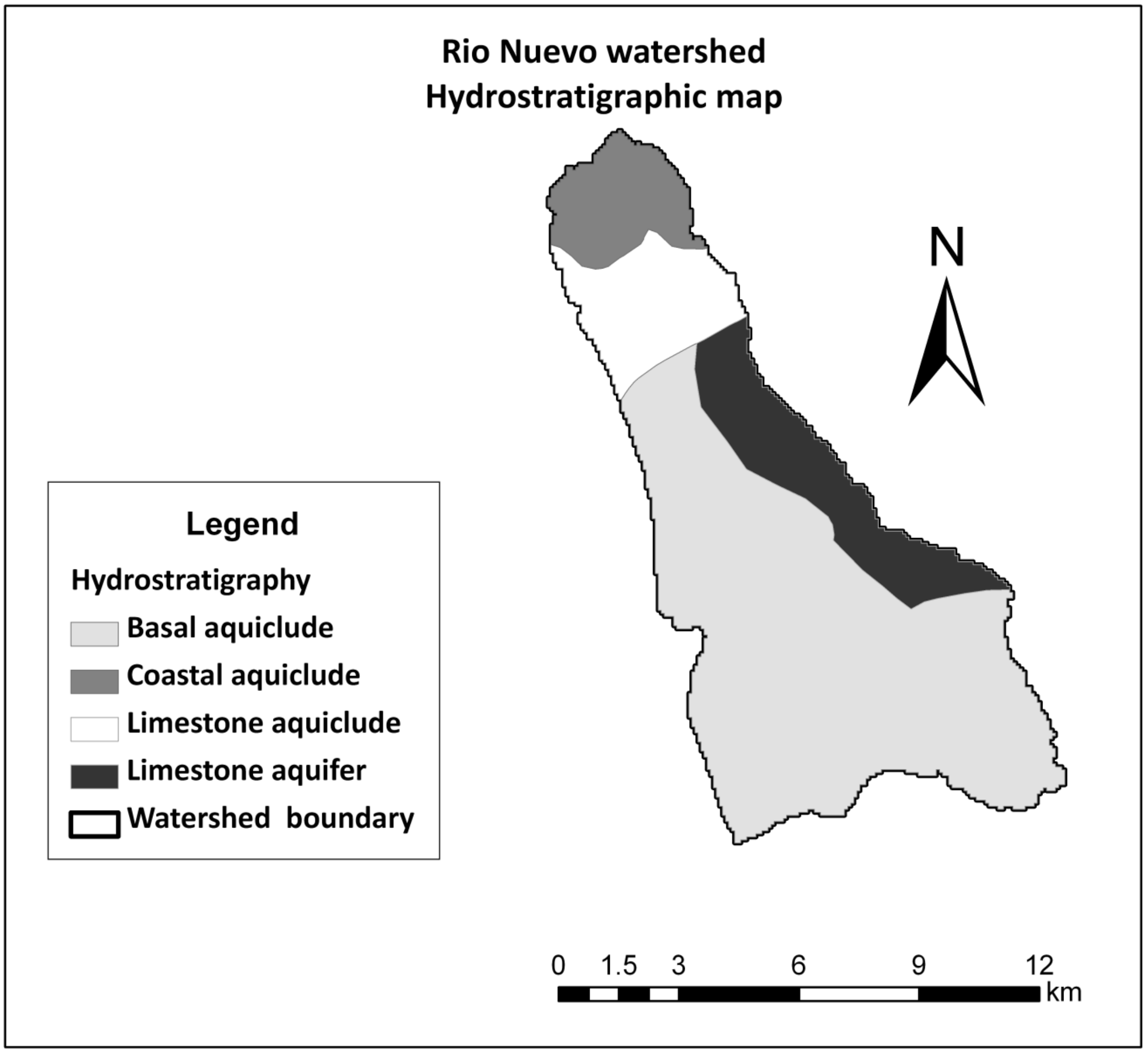


**Figure 5.3: Hydrostratigraphic map of Rio Nuevo watershed**

### 5.2.2 Model Inputs

SWAT requires land use data, soil type data, a digital elevation model (DEM), and optionally, stream network data (Neitsch et al., 2005). Each of these was used as input for the model. Table 5.4 shows the source of each digital data set. All digital datasets had a Lambert Conformal Conic Projection, and used a JAD 2001 Jamaica Grid projected coordinate system. SWAT requires daily precipitation data, as well as daily maximum and minimum temperature data (Neitsch et al., 2005). In addition, long term (at least 20 years) climatic data is needed in order for SWAT to simulate rainfall events.

**Table 5.4: Data inputs into SWAT**

| Data Type | Source |
|---|---|
| Digital Elevation Model (DEM) | Digital contours provided by the Jamaica Water Resources Authority (250 ft /76.2 m resolution) |
| 2001 Land Use | Forestry Department, Jamaica |
| Soils data | Rural Physical Planning Unit- Ministry of Agriculture |
| Stream network | Jamaica Water Resources Authority |

There were two rain gauges within the immediate area (but not within the bounds) of the watershed from which historical daily rainfall data ranging from a period of 2000 – 2007 was used. These rain gauges are operated by the Meteorological Service of Jamaica. In addition, there was one stream gauge on the Rio Nuevo, the location of which is also shown in Figure 5.4. Daily streamflow data was obtained from the Water Resources Authority for this stream for the period 2000 to 2007. Figure 5.4 also shows the stream network which was used. Lastly, both minimum and maximum daily temperatures were obtained for the Donald Sangster International Airport, as well as the Norman Manley International Airport, provided courtesy of the Meteorological Service of Jamaica.

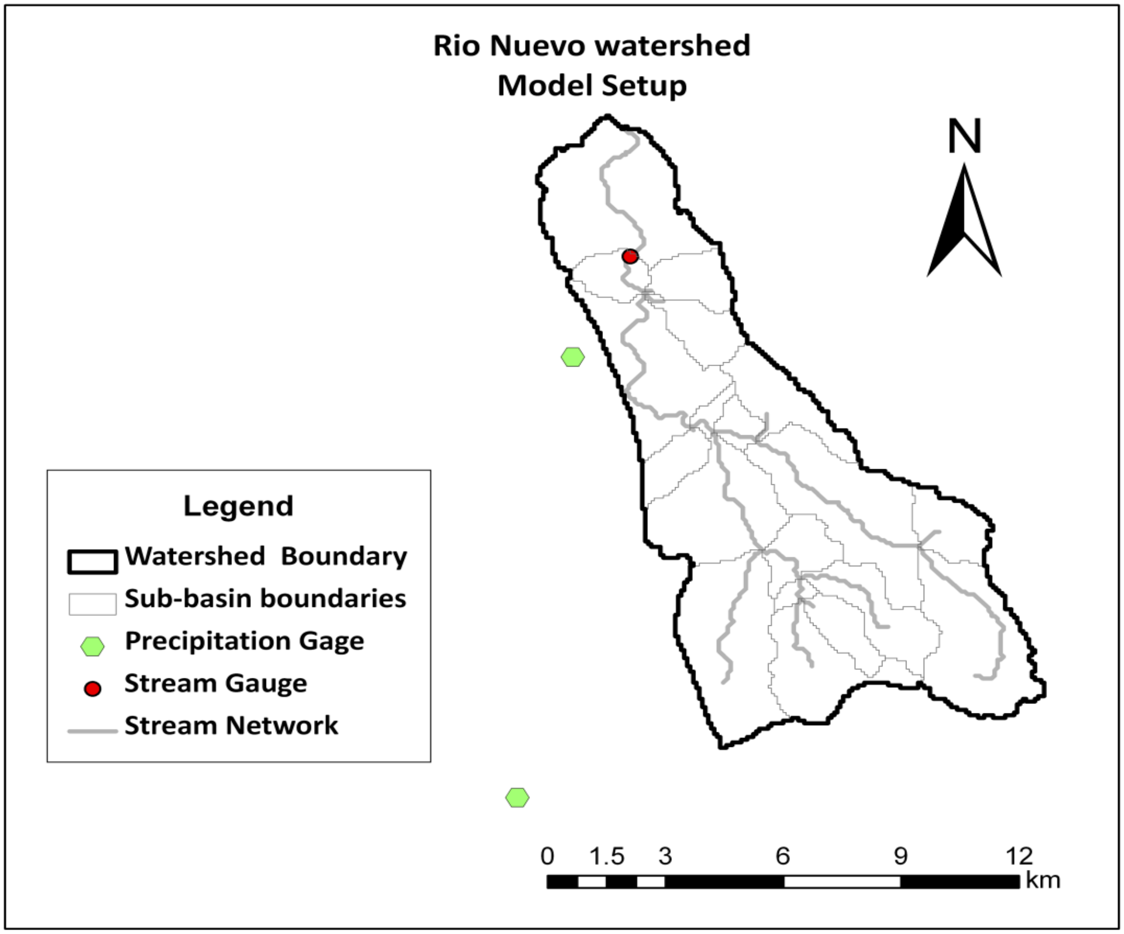


**Figure 5.4: Location of monitoring points and precipitation gauge**

The landuse classes did not exist previously in the SWAT database, and so new landuse classes were created, using all available information for each landuse. There were, however, several landuse parameters which were not available by measurement. Hence, these parameters were obtained from other similar landuse classes available in the SWAT database. All landuse parameters are shown in Table C.2.

The "Fields" and "Built-up" land uses were the only ones that were re-classified using pre-existing SWAT land uses. The Fields land use was redefined as Agricultural Row Crops (AGRR) in SWAT. However, this landuse was split into 4 sub-landuses: hot peppers, bananas, cabbages and tomatoes. These crops were chosen as they are grown throughout the entire region. The SWAT design team was most kind in providing the parameters for the hot peppers and bananas (Table C.2). The "Built-up" land use was reclassified as the pre-existing SWAT land use termed Residential medium/low density (URML). This pre-existing land use was chosen as the watershed is rural, and any industrial area would be minimal. An HRU threshold of 20% was chosen for land use. This was done in recognition of the spatial variability of the land use.

Despite the fact that there are 15 soil types in the watershed, only 9 were represented in the model. This is due to the fact that sufficient information (such as rooting depths and soil textures) was not available for all the soils. A description of the data available for each of the soil types is provided in Section C.1. This data was provided by the Rural Physical Planning Unit of the Ministry of Agriculture. In addition, a threshold of 15% of each hydraulic retention unit (HRU) was set for the model for soil types, meaning that once a soil type did not represent at least 15% of the sub-basin, then it was not represented in the model. This was done in order to capture the spatial variability of soil types throughout the watershed. Table C.3 shows the values used for all the SWAT parameters in this model.

Before the SWAT model could be used, the methods which the model would use to determine evapotranspiration, precipitation events, run-off, and stream routing needed to be determined and defined. The Preistley-Taylor method was used in order to determine evapotranspiration, while precipitation was simulated as a skewed normal distribution. The Soil Conservation Service (SCS) Curve Number method was used in order to determine run-off, while the Muskingum method was used for stream routing. These methods were chosen iteratively through the calibration process, in other words, the most accurate results were found when these methods were used.

Weather generator data

In order for SWAT to simulate relative humidity and wind speed, detailed statistical information on each of these parameters was required by the model. This information, along with other statistical information relating to precipitation and temperature, was compiled in an input table termed the Weather Generator Input Table. In order for relative humidity and wind information to be compiled, monthly average wind speeds, average daily solar radiation in the month, and average dew point temperature in the month, were required (Neitsch et al., 2004). Ideally this data would be available over a minimum period of 20 years. Unfortunately, this data could not be obtained by the researchers over any significant period of time for any area of Jamaica. Therefore, data for the Florida Keys was used instead, as this was the closest location for which weather generator statistical data was available in the SWAT database. The climatic data parameters are not presented due to the large amount of information. However, they are readily available in the SWAT database.

### 5.2.3 Simulation

The simulation process was divided into three main steps: setting up and running of the model, calibration, and validation. Simulation was performed over the years 2000 to 2007. Calibration was performed using streamflow data from 2002 to 2004, while validation was carried out using streamflow data from 2005 to 2007. Although the model was run for the years 2000 to 2007, the years 2000 and 2001 were not calibrated because of too much missing streamflow data. Once all the inputs were properly defined and integrated into GIS, the model was then run using the default SWAT parameters. In order to test the validity of the model, a water balance was performed in order to ensure that the outputs of the model were reasonable. The water balance was performed according to the following relationship:

$$\Delta SW = PCP - ET - PERC - LATQ - SURQ \qquad 5.1$$

Where:

$\Delta SW$ is the change in soil moisture (mm)
PCP is precipitation (mm)
ET is evapotranspiration (mm)
PERC is deep water percolation (mm)
LATQ is the lateral shallow sub-surface flow to the reach (mm)
SURQ is the surface runoff (mm)

The One at a Time (OAT) Sensitivity Analysis was conducted through a Sensitivity Analysis tool in SWAT. This analysis was performed in order to assess the quantitative effects of SWAT input parameters on the output. These parameters were related to different aspects of the water balance, including movement of soil moisture to shallow aquifers, base flow to streams, lateral movement of soil moisture to streams, evapotranspiration, and stream routing. A 0.05 parameter change for the OAT was set in SWAT, with the 10 intervals within the latin hypercube. All errors which were identified in the input data were rectified and resolved during the simulation process.

Calibration and Validation

In order to maximize the accuracy of the model, the results were then calibrated. In this process, the most sensitive model parameters determined from the OAT sensitivity analysis were identified. The parameters were changed with the assistance of the Manual Calibration tool in SWAT. The model parameters were changed in pre-determined intervals, and the magnitude of these intervals was relative to the magnitude of the parameters. Similarly to the sensitivity analysis, each parameter was adjusted one at a time. After each parameter was adjusted, the model was re-run, and the model performance quantitatively determined by the Nash-Sutcliffe efficiency (NSE), the percent bias (PBIAS) and the ratio of the root mean square error to the standard deviation of measure data (RSR), as developed by Moriasi et al. (2007). The NSE provides a quantitative indication of how well the plot of simulated data versus observed values fit a 1:1 line (Moriasi et al., 2007). The PBIAS is a measurement of the tendency of a simulated value to be smaller or larger than its observed counterpart. Lastly, the RSR gives an indication of residual variation, and incorporates the benefits of error index statistics (Moriasi et al., 2007).

Stream flow was used in order to compare the simulated to the observed results. It should be noted that the calibration was performed on a monthly basis. Any month for which three or more days of observed data was missing was not included in the model evaluation. This was done as missing data most likely represented high stream flows due to storm conditions. The omission of these stream flows from the determination of the monthly values would have significant effects on the monthly values, thereby throwing off the reliability of the observed data. Calibration was performed using stream flow data from 2002 to 2004. The months that were omitted from the calibration process due to missing data are January and September 2002, December 2003, January 2004, April to July and September to October 2004.

The validation process was performed using simulated and observed stream flow from 2005 to 2007. After the model was calibrated, the accuracy of the model was determined during the validation process. For this process, the monthly simulated stream flow results for 2005 to 2007 were compared to the observed monthly stream flow results for the same period. All the afore-mentioned model evaluation parameters were also used in the validation process. Performance ratings (unsatisfactory, good, excellent) for each of these statistics are available in Moriasi et al. (2007). These guidelines were used for both the calibration and validation process in order to assess the effectiveness of both processes, and are shown in Table B.1.

## 5.3 Results

### 5.3.1 Calibration

The calibrated parameters, along with their descriptions (obtained from Neitsch et al. (2004)) are shown in Table 5.5 below. The calibrated and uncalibrated values are shown in Table 5.6.

**Table 5.5: Calibrated parameters**

| Parameter | Units | Description |
|---|---|---|
| Threshold water depth in shallow aquifer for return flow (GWQMN) | mm | Groundwater flow to the reach is allowed only if the depth of water in the aquifer is equal to or greater than GWQMN |
| Soil Evaporation Compensation Factor (ESCO) | - | This coefficient defines the depth of soil from which water can be taken from the soil in order to meet evaporative demand. |
| Groundwater delay (GW_DELAY) | days | The time lag between when water exits the soil profile and enters the shallow aquifer |
| Deep aquifer percolation fraction (RCHDP) | - | The fraction of percolation from the root zone which recharges the deep aquifer |
| Baseflow recession constant (ALPHA_BF) | days | An index that represents the response of groundwater to changes in recharge |
| Groundwater 'revap' coefficient (GW_REVAP) | - | This coefficient defines the restrictions relating to the movement of water from the shallow aquifer to the root zone |
| Threshold water depth in shallow aquifer for deep percolation to occur (REVAPMN) | mm | A threshold depth, under which movement of water from the shallow aquifer to the unsaturated zone is not allowed |

Table 5.6 shows the calibrated parameters, including the original (uncalibrated) parameter values, as well as the calibrated parameter values.

**Table 5.6: Calibrated and uncalibrated values for calibration parameters**

| Parameter | Range | Unit | Un-calibrated | Calibrated |
|---|---|---|---|---|
| GWQMN | 0-5000 | mm | 0 | 1 |
| ESCO | 0-1 | - | 0.95 | 0.99 |
| GW_DELAY | 0-500 | days | 31 | 35 |
| RCHDP | 0-1 | - | 0.05 | 0.15 |
| ALPHA_BF | 0-1 | days | 0.048 | 0.9 |
| GW_REVAP | 0.02-0.2 | - | 0.02 | 0.12 |
| REVAPMN | 0-500 | mm | 1 | 2 |

### 5.3.2 Surface flows

The model output was obtained for the same location along the stream reach as the actual stream gauge. The observed and simulated stream flows were then compared on a monthly basis for both the calibration and validation time periods. During the calibration period, SWAT under-estimated the two large events that occurred in October 2003 and March 2004. During the validation period, SWAT over-estimated some of the run-off events that occurred in January and July 2005, as well as November 2007. Figures 5.5 and 5.6 show the calibrated and validated streamflow hydrographs, showing observed and simulated flows.

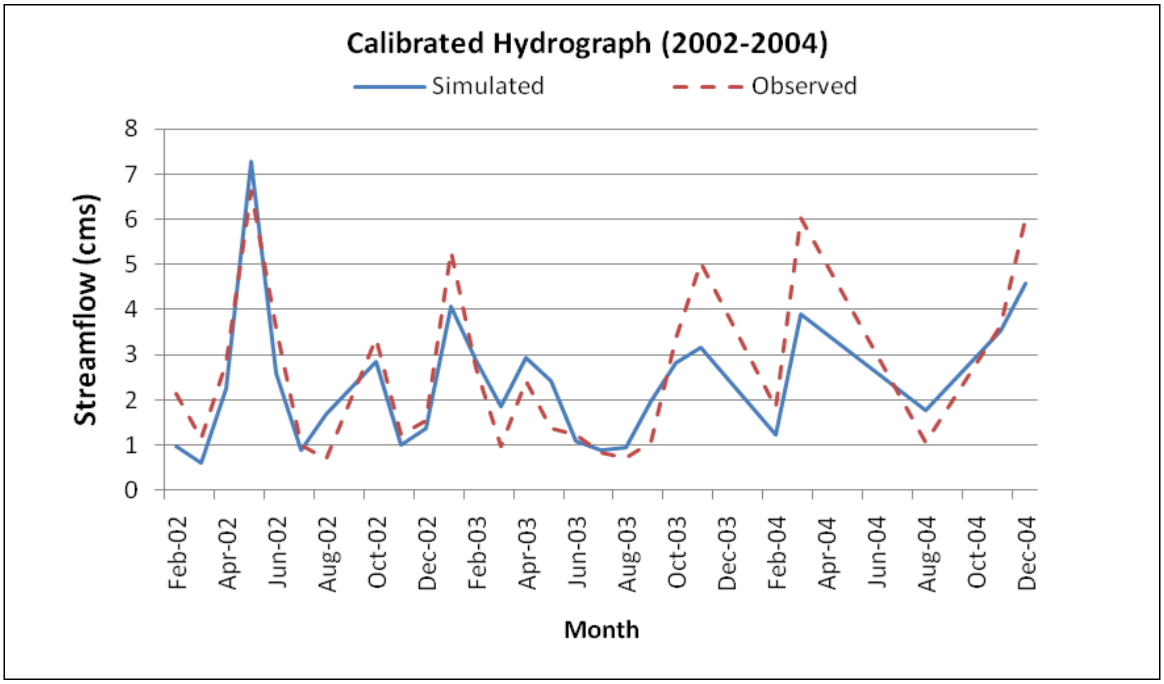


**Figure 5.5: Calibrated hydrograph for Rio Nuevo**

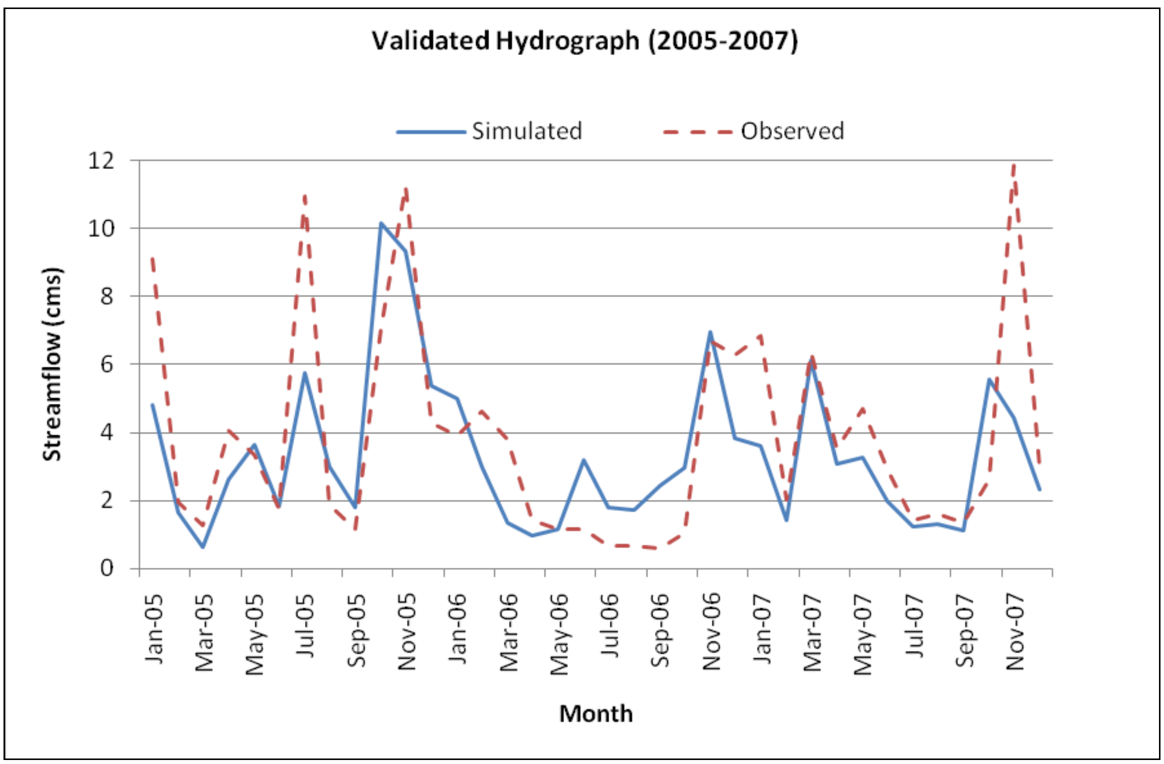


**Figure 5.6: Validated hydrograph for Rio Nuevo**

### 5.3.4 Model Evaluation

The calibration and validation performance ratings are shown in Table 5.7 below. A table showing the general calibration performance ratings is shown in Table C.1. According to these ratings, the performances of all three indices (NSE, PBIAS and RSR) are very good. If the same standards are applied to the validation indices, then the NSE value is satisfactory, while the RSR is in the unsatisfactory range. Although the RSR is in the unsatisfactory range however, it is very close to the bound of the satisfactory/ unsatisfactory range (0.70). The validation performance is generally expected to be less than the calibration performance (Moriasi et al., 2007), therefore the validated RSR parameter will therefore be treated as satisfactory for the purposes of this research. It must also be noted that although the validated NSE is in the satisfactory range, it is on the verge of unsatisfactory. This is a low value, but again, as the standards in Table C.1 are meant for calibrated parameters, which are expected to be higher than validated parameters, this NSE value of 0.504 is deemed as acceptable for this research. The range and ideal values of each of the performance indicators were obtained from Moriasi et al. (2007).

**Table 5.7: Calibration and validation model performance ratings**

| Performance Indicator | Calibrated | Performance Rating | Validated | Performance Rating | Range | Ideal |
|---|---|---|---|---|---|---|
| **NSE** | 0.758 | Very Good | 0.504 | Satisfactory | - ∞ to 1 | 1 |
| **PBIAS** | 9.496 | Very Good | 12.767 | Good | - ∞ to ∞ | 0 |
| **RSR** | 0.492 | Very Good | 0.704 | Satisfactory | 0 to a large positive number | 0 |

## 5.4 Discussion

Overall, the model performed satisfactorily, achieving an NSE of 0.76 for calibration, and 0.50 for validation. This is in keeping with results from other studies, which have reported successful applications of SWAT in other developing countries. It was applied in Ethiopia by Mekonnen et al. (2009), resulting in $R^2$ coefficients of 0.88

and 0.83 for calibration and validation respectively for streamflow. SWAT was also successfully applied in Tunisia, with NSE coefficients of 0.73 and 0.43 for calibration and validation respectively for streamflow (Ouessar et al., 2009).

The fact that the rain gauges used in the model were not actually in the watershed would have negatively impacted the results. In addition, land use would have changed over time. Unfortunately, the most recent landuse data which was available for this research was from 2001. In addition, weather data from Florida was used in order for SWAT to simulate relative humidity and wind conditions. There are orographic effects which would affect the relative humidity and wind conditions within the Rio Nuevo watershed. However, the Florida Keys are relatively flat, resulting in different characteristics for these climatic conditions. The inherent error that exists in the input data would have resulted in a compounded error throughout the modelling process.

An attempt was made to improve these results through the calibration process. There are no actual measurements relating to groundwater flow within the watershed, and so all the calibration results are based simply on which values provide the optimal model response. The question therefore arises as to whether or not these calibrated values are representative of what actually happens within the watershed. Due to a lack of published data on groundwater flow, not only within the larger Blue Mountain North watershed, but within the island, the assumption must be made that the calibrated values are indeed within reasonable ranges for Jamaican sub-surface systems.

Through calibration, the value for the baseflow recession constant (ALPHA_BF) was increased. This increase in ALPHA_BF signified an increased sensitivity of groundwater flow to changes in groundwater recharge. There was a significant increase in this parameter from 0.048 to 0.9. This is especially significant as the range of ALPHA_BF is from 0 to 1, with 1 expressing the highest groundwater flow response. Likewise, the Soil Evaporation Compensation Factor (ESCO) was increased, resulting in an increased depth from which water could be taken in order to meet evapotranspiration demand. The groundwater "revap" coefficient (GW_REVAP) was also significantly increased from 0.02 to 0.12, which allows for easier movement of water from the shallow aquifer to the root zone. The increases in ALPHA_BF, ESCO and GW_REVAP all imply that throughout the watershed, surface and groundwater interactions are actually quite important. This is despite the limited surface and groundwater interactions that can take place throughout the watershed due to the aquicludal hydrostratigraphy.

GW_DELAY (the time lag between when water exits the soil profile and enters the shallow aquifer) was also increased from 31 days to 35 days. Any attempts to lower this value during the calibration process resulted in worse model performance. As the major part of the watershed is indeed aquiclude, the increase in delay time is justified. There was a minimal increase (from 0 to 1 mm) in the GWQMN, which is the threshold depth in the shallow aquifer required for groundwater flow to the reach. Likewise, there was minimal change (1 to 2 mm) in REVAPMN, which is the threshold depth in the shallow aquifer for deep percolation to occur. Both of these values imply that flow occurs very easily between the groundwater systems and surface water systems.

It is important to note that neither the Curve Numbers, nor the available water capacities of the soils was calibrated. These parameters tend to be very important calibration parameters. Many SWAT studies have shown that the calibration of these parameters results in improved model performance (Govender and Everson, 2005; Zhang et al., 2008). However, even though the sensitivity analysis showed these parameters as highly sensitive, changes that were made to these parameters showed no improvement in model performance. A similar result was seen in the study performed by Mulungu and Munishi (2007). This result is one more indicator pointing to the importance of sub-surface interactions within this watershed.

The results of the calibration process might seem counter-intuitive, considering the fact that the major portion of the watershed is underlain by either basal, coastal or limestone aquiclude. However, 15 % of the watershed is karstic, which adds a level of complexity that is difficult to simulate. The possible effects of karsticity on the entire watershed dynamics are discussed in the following section.

### 5.4.1 Model performance and karsticity effects

As mentioned in the results, SWAT underestimated some of the peak flow events with the largest under-estimation resulting in a standard error of 35.7 % during the calibration period (2002-2004). During the validation period, SWAT over-estimated some of the peak flow events (2005-2007), with standard errors as high as 62.8 % during these events. In speaking with the Meteorological Service of Jamaica, these peak flows were caused by tropical storms, resulting in conditions which would have been difficult for the model to simulate.

However, this model is meant to be used in the context of irrigation management during water scarce conditions. As such, the ability of SWAT to simulate low flows is more relevant to this context than the ability of SWAT to simulate storm flows. During storm conditions, evapotranspiration losses will be replaced by rainfall, and irrigation demand is no longer an issue. However, periods of low flow are a result of low rainfall, and it is during these times that irrigation demand becomes an issue. Unfortunately, SWAT at times had difficulty simulating some low flow conditions, with an over-estimation of a period of low flow occurring in March 2003 during calibration, and an over-estimation of 320% occurring during a very dry period in September 2006. Overall though, the simulation of low flow events was satisfactory (Figures 5.5 and 5.6).

It is likely that the geomorphology of the watershed plays a significant role in the inability of the SWAT to capture all of the low-flow events. The karstic portion of the watershed leads to complex interactions between surface and groundwater. The fact that the vast majority of the parameters which were calibrated were in relation to groundwater (baseflow release factors and groundwater delay factors), signifies that the karstic aquifer affects the entire dynamic of the watershed. This highlights the fact that the interaction between surface and groundwater plays an important role in the over-all dynamics of the watershed.

Salerno and Tartari (2009) did some work investigating the use of wavelet analysis (WA) along with SWAT, in simulating streamflow in a karstic watershed. They highlighted the disadvantage that deterministic models such as SWAT face when modelling karstic environments. The use of these kinds of models lead to over or under-estimation of streamflow, due to their inability to accurately compute contributions to streamflow from sub-surface circulation. It is especially difficult to simulate streamflows in karstic environments, as the component of flow coming from the karst conduits cannot be directly measured (Salerno and Tartari, 2009). The authors found that the use of wavelet analysis was able to circumscribe the problem. Therefore, the coupling of SWAT with a groundwater assessment tool or model can result in significant reduction of the karstic effects. The wavelet analysis was not done in this study simply due to the lack of measured groundwater data. However, due to the role which this aquifer is likely to have played in these interactions, it is recommended that future studies in Jamaica using SWAT in karstic watersheds use tools such as wavelet analysis to improve results, and circumscribe the karstic effect. In order for this to be done, groundwater characterization studies should be done, in order to allow for calibration and validation of the groundwater assessment tools.

### 5.4.2 Use of SWAT in agricultural water scarcity management

Chapters 3 and 4 described how soil moisture can be predicted and applied in order to determine irrigation requirements for both vegetable crops and sugarcane. However, the use of a modelling tool such as SWAT can be pivotal in irrigation planning, especially in light of water scarce conditions. SWAT can be used in order to determine water savings from different water management scenarios (Santhi et al., 2005). This is especially important in light of the competing uses for water among different watershed stakeholders. The irrigation planning process requires a basin wide perspective, as water supplies cross both town and parish boundaries. What this research sought to do therefore is to introduce SWAT as a tool for carrying out this type of quantitative analysis on a watershed level in Jamaica.

In order to demonstrate this process, the results from SWAT were applied to sub-basin 13 of the Rio Nuevo watershed to determine irrigation applications using a sprinkler system. The sprinkler efficiency was 0.75 (Table A.6). This sub-basin was chosen as it is in the area of the watershed where the greatest concentration of agricultural activity takes place. The total area of the sub-basin is 8.22 $km^2$, and 67.12 % of the sub-basin is under agriculture. Thus the area of the watershed under agricultural development is 5.52 $km^2$. All the necessary parameters of the water balance needed in order to determine the irrigation requirements on a monthly basis were available from the SWAT results. The calculations were done for the period 2000 to 2007, for the dry months January to April. The methodology applied in determining the irrigation requirements are the same as those provided in Chapter 3 (Equation 3.7). The water balance components are shown in Table 5.8, while the residual streamflows for 50, 25 and 10% irrigated agricultural area is shown in Table 5.9. These values were used as 100% of the agricultural area will never be irrigated, and these percentages were deemed as reasonable scenarios. In order to determine the streamflow in millimetres, the streamflow in cubic meters per second was divided by the relevant area of irrigation application in the watershed, with the appropriate unit conversion factors applied.

As mentioned previously in this manuscript, there were significant agricultural losses due to drought in the years of 2000 and 2001. From the results in Table 5.8, it is apparent that the effects of this drought were also felt in the Rio Nuevo watershed. Note that in 2000, there was not enough streamflow to satisfy the irrigation demands in January, for all three irrigation distributions. Likewise, in March of 2000, there was not enough streamflow to satisfy the irrigation demands for the 25 and 50% irrigation distributions. In 2001 in the month of March, there was also not enough streamflow to satisfy the irrigation demands for 50% irrigation distribution, and barely enough to satisfy the demands in April.

Municipal, industrial, domestic and environmental flows were taken into consideration for these calculations. Although these are difficult to quantify for this watershed based on available data, there are published values on acceptable percentages for approximating these flows. The actual streamflow values are shown in Table 5.8, but only 63% of the streamflows were used in the calculations for determining residual streamflow, as shown in Table 5.9. The percentage of 63% was obtained as a fraction of 30% is in general required for environmental flows in the Caribbean region (Smakhtin et al., 2004). In addition however, a fraction of 20 to 50% of the mean annual runoff (approximated as streamflow in this case) should be allocated to industrial, municipal, domestic and environmental flows. A median value of 35% was chosen for this allocation, as the watershed is rural and the industrial flows would not be high. In Jamaica however, non-agricultural uses account for 20% of the demand, and so 80% of the demand goes towards irrigation (WRA, 2010). Therefore, of the 35% allocated to municipal, industrial, domestic and agricultural flows, 28% of that is available for irrigation. Therefore, in total, 37% of the streamflow is not available for irrigation, resulting in the value of 63% which was used in the calculations to obtain the values presented in Table 5.9.

**Table 5.8: Water balance components in sub-basin 13 as determined with SWAT**

| Year | Month | Effective precipitation (mm) | Actual evapo-transpiration (mm) | Soil moisture (mm) | Irrigation Requirement (sprinkler) (mm) | Streamflow (mm) |
|---|---|---|---|---|---|---|
| 2000 | Jan | 0.00 | 5.52 | 7.96 | 7.36 | 0.000 |
| | Feb | 6.06 | 8.65 | 9.69 | 3.46 | 1.863 |
| | Mar | 7.25 | 15.83 | 5.75 | 11.44 | 1.457 |
| | Apr | 18.58 | 29.81 | 0.54 | 14.98 | 12.896 |
| 2001 | Jan | 0.00 | 19.65 | 32.65 | 26.20 | 53.179 |
| | Feb | 0.00 | 9.11 | 23.54 | 12.15 | 18.997 |
| | Mar | 7.38 | 28.35 | 6.94 | 27.96 | 10.077 |
| | Apr | 18.26 | 23.03 | 11.57 | 6.36 | 7.214 |
| 2002 | Jan | 138.22 | 34.31 | 57.48 | 0.00 | 578.943 |
| | Feb | 15.99 | 31.91 | 48.77 | 21.24 | 114.136 |
| | Mar | 52.52 | 72.92 | 37.00 | 27.19 | 85.796 |
| | Apr | 53.05 | 77.24 | 9.59 | 32.25 | 803.520 |
| 2003 | Jan | 89.42 | 30.52 | 49.53 | 0.00 | 1381.977 |
| | Feb | 59.89 | 29.07 | 36.26 | 0.00 | 499.709 |
| | Mar | 57.13 | 53.51 | 49.30 | 0.00 | 569.707 |
| | Apr | 133.39 | 113.85 | 13.59 | 0.00 | 694.148 |
| 2004 | Jan | 45.52 | 33.82 | 50.45 | 0.00 | 563.874 |
| | Feb | 55.23 | 34.85 | 57.91 | 0.00 | 207.710 |
| | Mar | 193.23 | 90.45 | 53.55 | 0.00 | 887.615 |
| | Apr | 83.21 | 95.97 | 21.76 | 17.02 | 522.555 |
| 2005 | Jan | 67.27 | 30.24 | 42.80 | 0.00 | 1280.868 |
| | Feb | 2.64 | 15.41 | 33.27 | 17.03 | 298.950 |
| | Mar | 0.00 | 24.33 | 8.95 | 32.43 | 115.351 |
| | Apr | 110.13 | 53.40 | 13.81 | 0.00 | 657.205 |
| 2006 | Jan | 89.36 | 35.95 | 52.81 | 0.00 | 1115.595 |
| | Feb | 72.48 | 33.17 | 58.38 | 0.00 | 774.840 |
| | Mar | 0.00 | 44.02 | 14.26 | 58.69 | 199.349 |
| | Apr | 40.93 | 53.79 | 5.34 | 17.16 | 187.828 |
| 2007 | Jan | 71.53 | 30.88 | 40.29 | 0.00 | 879.837 |
| | Feb | 0.00 | 10.44 | 29.85 | 17.94 | 353.150 |
| | Mar | 212.51 | 56.06 | 53.45 | 0.00 | 1461.211 |
| | Apr | 96.18 | 91.47 | 33.33 | 0.00 | 450.175 |

**Table 5.9: Residual streamflow for 50, 25 and 10% irrigated agricultural area**

| Year | Month | Residual Streamflow for 50 % Irrigated Area | Residual Streamflow for 25 % Irrigated Area | Residual Streamflow for 10 % Irrigated Area |
|---|---|---|---|---|
| **2000** | Jan | 0.0 | 0.0 | 0.0 |
| | Feb | 11.8 | 35.7 | 107.5 |
| | Mar | 0.0 | 0.0 | 9.2 |
| | Apr | 1.3 | 17.5 | 81.2 |
| **2001** | Jan | 40.8 | 107.8 | 334.9 |
| | Feb | 11.8 | 35.7 | 107.5 |
| | Mar | 0.0 | 0.0 | 63.5 |
| | Apr | 2.7 | 11.8 | 45.4 |
| **2002** | Jan | 729.5 | 1458.7 | 3645.6 |
| | Feb | 122.6 | 266.4 | 697.8 |
| | Mar | 80.9 | 189.0 | 540.3 |
| | Apr | 980.2 | 1992.3 | 5059.8 |
| **2003** | Jan | 1741.3 | 3482.1 | 8702.3 |
| | Feb | 629.6 | 1259.3 | 3148.2 |
| | Mar | 717.8 | 1435.4 | 3587.4 |
| | Apr | 874.6 | 1749.0 | 4371.1 |
| **2004** | Jan | 710.5 | 1420.7 | 3550.7 |
| | Feb | 261.7 | 523.4 | 1308.6 |
| | Mar | 1118.4 | 2236.5 | 5589.3 |
| | Apr | 641.4 | 1299.6 | 3290.5 |
| **2005** | Jan | 1613.9 | 3227.3 | 8065.6 |
| | Feb | 359.7 | 736.3 | 1866.4 |
| | Mar | 112.9 | 258.2 | 726.4 |
| | Apr | 112.9 | 258.2 | 726.4 |
| **2006** | Jan | 1405.6 | 2810.9 | 7024.9 |
| | Feb | 976.3 | 1952.6 | 4881.5 |
| | Mar | 192.5 | 443.6 | 1255.3 |
| | Apr | 219.5 | 456.1 | 1182.8 |
| **2007** | Jan | 1108.6 | 2216.9 | 5540.3 |
| | Feb | 427.0 | 872.0 | 2206.9 |
| | Mar | 1841.1 | 3681.7 | 9201.2 |
| | Apr | 567.2 | 1134.3 | 2834.8 |

The results show that during periods of water scarcity, there is not enough streamflow to satisfy irrigation demands in this sub-basin. During all the other non-drought years however, enough streamflow was indeed available to meet the irrigation demands (not taking into account other demands). Therefore, planning needs to take place in order to ensure that should a period of similar drought intensity recur, there are contingency plans in place to manage and supply water. Improving water conservation practices throughout the watershed would also be an important part of this process. It is important to note that there was no way of validating the soil moisture values or the evapotranspiration values that were simulated by SWAT. Therefore, care should be taken when applying these results.

Local stakeholders can use the results of this research to improve irrigation planning. The results from the model show that during dry years, the ability to irrigate is severely limited, as there is simply not enough streamflow to meet the crop needs. Plans to ensure that there is adequate irrigation capacity in the watershed need to be developed and continually assessed. Researchers and planners should use the results of this research to develop and assess their watershed management plans by taking into account the issues that were encountered in this research. There is much potential for the use of hydrologic models in Jamaica, but the issues of data availability needs to be addressed. Steps should be taken to ensure that parameters such as relative humidity and wind speed can be measured for the particular watershed that is being modelled. There were issues with the karsticity of the watershed, and as this is a widespread issue in Jamaica, it needs to be realistically considered. More research must be done on finding the most appropriate tools for modeling the watershed based on the complex groundwater characteristics of many of the Island's watersheds.

The aim of this research was not to carry out the actual management scenarios, but to determine if the potential existed for this tool to be used for that purpose. In light of this, no management scenarios were carried out with this model. However, in future research, this model can be used in order to gain an improved understanding of the water balance, as the determination of irrigation amounts for normal precipitation conditions is just one step in the process of managing water resources. The model can be used in order to assess water productivity and crop water use. In addition, it can be used in order to determine which cropping system would result in the most efficient water use, through the assessment of evapotranspiration losses. In short, this calibrated model can be used for analyzing different management scenarios for better crop management practices and irrigation planning.

There are some limitations to the results presented in this chapter. Ideally, the ability of the SWAT model to represent conditions in the Rio Nuevo watershed would have been compared with other models, such as artificial neural networks. In addition, SWAT would have ideally been tested on two different watersheds, in order to better evaluate the use of the model in a Jamaican context. However, the purpose of this research is to serve as a first step to use of hydrologic models for planning purposes in Jamaica, and subsequent research can explore these issues in far more detail.

A significant problem with the use of hydrological models in Jamaica lies not only in a severe shortage of data (hydrologic, climatic, and agricultural), but also a shortage of human and financial resources. However, models such as SWAT provide such powerful tools, that further investment into the future collection of data, and the future development of human resources, would go a long way in ensuring that Jamaica can adequately plan for the changing climatic conditions. To this end, values for the majority of the parameters used in the development of this model have been published in Appendix C of this manuscript, in order to facilitate the development of this model for other locations in Jamaica.

### 5.4.3 Uncertainty Analysis

Watershed models suffer from large model uncertainties, and these can be divided into conceptual model uncertainty, input uncertainty and parameter uncertainty (Abbaspour, 2008). Conceptual model uncertainty represents disparities between the processes in the model, and the processes in the watershed. Input uncertainty is as a result of errors in input data. This could be climatic data, land use data, streamflow data etc. Lastly, parameter uncertainty represents the idea that several different processes can give rise to different parameters that end up producing the same output signal (Abbaspour, 2008). In order to deal with these uncertainties, an uncertainty analysis can be performed with the model parameters in order to quantify the uncertainty bounds, allowing for more informed decision making. There are several methods of doing this, including the Generalized Likelihood Uncertainty Estimation (GLUE) (Beven and Binley, 1992) and Parameter Solution (ParaSol) (Van Griensven and Meixner, 2007) (Abbaspour, 2008).

While it would have been ideal for this to have taken place for this particular SWAT model, due to limitations on the scope of the research, an uncertainty analysis was not done. This being said however, the performance of an uncertainty analysis should be a key focus for subsequent research on this project.

## 5.5 Conclusions

A SWAT hydrological study was undertaken for the Rio Nuevo watershed in St. Mary's parish. Streamflow was simulated, and the model was calibrated using observed streamflow from 2002 to 2004, and validated using observed streamflow from 2005 to 2007. An NSE correlation coefficient of 0.76 was obtained for calibration, while a coefficient of 0.50 was obtained for validation. Surface-groundwater interactions played a very important part in the hydrologic dynamics of this watershed, despite the fact that the majority of this watershed is underlain by basal aquiclude. As a result, the most critical calibration parameters included GWQMN, RCHDP, ESCO and ALPHA_BF.

SWAT had some difficulties in simulating high-runoff events. Despite this, it has been determined that SWAT is a suitable model for use in simulating streamflow in this watershed, and holds much potential for future agricultural water resources planning, not only in this sub-basin, but also in other watersheds in Jamaica. It is important that pre-emptive action be taken towards water scarcity planning, and SWAT provides a very important tool for achieving this, as it can be used to determine strategies which could be put into place in order to maximize agricultural water savings. The land use and soil parameters that were used for this model are published with this paper, with the intention that they be used as a reference in the development of future hydrologic simulations within the island.

SWAT was used in an agriculturally intensive sub-basin of the Rio Nuevo watershed in order to determine whether adequate streamflow was available for irrigation purposes in the dry months of the year. In the drought years of 2000 and 2001, sufficient streamflow was not available for particular months of the year. As environmental flows and human demands were also not taken into consideration, it may also be the case that the residual streamflow is not sufficient to meet these demands in other years, and therefore 2000 and 2001 may not be the only years for which water scarce conditions were experienced. Therefore, suitable planning needs to take place in order to ensure that in the future, agricultural losses due to drought are minimized.

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# CHAPTER 6: Summary and conclusions

## 6.1 Summary

Planning for water scarce conditions in Jamaica is becoming increasingly important in light of growing demands on the Island's water resources, as well as the uncertainty in water resources dynamics that will be brought about by climate change. In light of this, this research set out to develop tools that will facilitate this planning in an agricultural context. Irrigation demands were determined for vegetables and sugarcane for three study sites, for typical soil moisture conditions, as well as water scarce conditions. Drought indices were developed, which were then related to available soil moisture values. These soil moisture values can then be used to determine irrigation demands during different severities of drought. Lastly, the Soil and Water Assessment Tool (SWAT) was developed, in order to determine whether or not this tool was appropriate for use within the Jamaican context for use in water management planning.

Both the Standardized Precipitation Index (SPI), as well as the Normalized Difference Vegetation Index (NDVI) were developed for three study sites: Savanna-la-mar in the parish of Westmoreland, Beckford Kraal in the parish of Clarendon, and Serge Island in the parish of St. Thomas. Both of the indices were compared to available soil moisture, in order to develop relationships between the index values and soil moisture. The NDVI only had good correlations to soil moisture in two months of the year for each site. However, the short term (one to three) month SPI can be used during the dry months of the year in all three locations for determining available soil moisture in water stressed conditions. Irrigation demands were determined for the Moderately Dry and Severely Dry SPI categories.

Irrigation planning data for three locations was determined. The irrigation requirements for sugarcane and vegetables were determined for using average monthly available soil moisture. In addition, a seasonal rainfall analysis was done for the seasons entailing the months of January to April, and May to August. These values have also been published in this manuscript.

Lastly, in order to move past reactive responses to drought, the SWAT model was built for the Rio Nuevo watershed, in the parish of St. Mary. This model provides a powerful tool for agricultural irrigation planning, and can be used in order to obtain a greater understanding of the water balance. SWAT performed well for the simulation of streamflow, and the model results were applied to an agricultural area within the watershed to evaluate streamflow availability during water scarce conditions. It was found that in non-drought years, there is some streamflow for irrigation. However, in particular months of the drought years of 2000 and 2001, there was a deficit of streamflow. Municipal, industrial and environmental flows were not considered, and as such, 2000 and 2001 might not be the only years in which water stressed conditions were experienced within the watershed.

## 6.2 Conclusions

The SPI was found to have reasonable correlations to soil moisture for particular months of the year for all three areas. It was noted that the best correlations were found in dry months, suggesting that the soil moisture responds much more easily during dry periods than wet periods. In addition, it was found that for Savanna-la-mar, as well as Beckford Kraal, the three month SPI had better correlations than the one month SPI, while in Serge Island, the one month SPI had better correlations than the three month SPI. Therefore, for both Savanna-la-mar and Beckford Kraal, the three month SPI is the most suitable indicator for agricultural drought, while in Serge Island, the one month SPI is the most suitable indicator of agricultural drought. The NDVI however, was found to have the best correlations for varying months in the period of January to April, for all three sites. Similarly to the SPI, it has the best correlations to soil moisture during the driest periods of the year.

It was found that, in general, the months of January to April, and July to August, required the largest amount of irrigation. These results are reasonable in light of the fact that these are also the driest months of the year. Lastly, It was found that the SWAT model was capable of simulating streamflow in the Rio Nuevo sub-basin, with a Nash-Sutcliffe Efficiency of 0.76 for calibration and 0.50 for validation. The specific conclusions that have been drawn from this study are outlined below.

i. Serge Island requires the most irrigation, with sugarcane requiring irrigation throughout the entire year except for the months of September to December for average soil conditions. Vegetables require irrigation every month except for the wettest months of May, September, October and November. For Savanna-la-mar, only the months of December, as well as February through to April require irrigation for vegetables, whereas irrigation for sugarcane is required through the month of February. Lastly, for Beckford Kraal, March, April, July and August require irrigation for vegetables, while sugarcane needs to be irrigated July through to August.

ii. Both Savanna-la-mar and Beckford Kraal had the best correlations using the three month SPI. Savanna-la-mar had these correlations in the months of February to June, while Beckford Kraal had these correlations from February to June, as well as September. Serge Island only saw these correlations for the months of April and March, as well as August. This is most likely related to the fact that a sandy loam soil was used for the Serge Island site, loam and clay soils were used for the Savanna-la-mar and Beckford Kraal sites respectively.

iii. The SPI correlates best to drier months of the year, as the soil moisture has a much greater response to changes in precipitation than in wet months when it is almost constantly at field capacity.

iv. Short term (one month and three month) SPIs are best for monitoring agricultural drought, with the one month SPI corresponding best to soil moisture for Serge Island, and the three month SPI having the best relationship with soil moisture for Savanna-la-mar and Beckford Kraal.

v. The NDVI had statistically significant, reasonable correlations with for the months of January and March in Savanna-la-Mar, January and April in Beckford Kraal, and January and February in Serge Island. Similarly to the SPI, it has much higher correlations with soil moisture in dry months than in wet months. This supports the idea that soil moisture, and therefore vegetation, will have a far greater response to changes in precipitation in dry months, than in wet months.

vi. Due to the limited months for which the NDVI was found to have correlations with available soil moisture, it would not be a suitable index for monitoring agricultural drought. However, if this study is done for other areas, much better correlations might be seen.

vii. For both the Savanna-la-mar and Beckford Kraal sites, a soil available water content of zero occurs during the months of March and April at the moderately dry SPI classification. However, it occurs at the Severely Dry classification for the other months for which good correlations between the SPI and soil moisture were found. This demonstrates the fact that March and April are the months of the year in which the available soil moisture reserves are at their lowest. Although no good correlation was found for the month of April, a soil available water content of zero occurred in the Moderately Dry category for both February and March, while occurring in the Severely Dry category in August.

viii. SWAT can be used to model streamflow in the Rio Nuevo basin, as an NSE coefficient of 0.76 was obtained for calibration, and 0.50 was obtained for validation. The PBIAS, and RSR were also used as model performance evaluators, and these also indicated satisfactory model performance.

ix. SWAT had difficulty simulating peak run-off events in both the calibration and validation periods. This is likely due to the presence of karstic aquifer in the watershed, which constitutes 15% of the watershed.

x. The parameters which were calibrated for SWAT are the GWQMN, GW_Delay, RCHDP, ESCO, ALPHA_BF, GW_REVAP and REVAPMN. All of these, apart from ESCO, relate to the movement of groundwater. This is interesting in light of the fact that 85% of the watershed is basal aquiclude, which precludes the movement between soil moisture and groundwater. However, it highlights the fact that the interaction between surface and groundwater plays an important role in the over-all dynamics of the watershed.

xi. During the drought periods of 2000 and 2001, there was not enough streamflow to provide the irrigation requirements in sub-basin 13 of the Rio Nuevo watershed, during the dry months of January to April in 2000, and the month of March in 2001. It could also very well be the case that there is not sufficient water for irrigation in other years since other water demands were not taken into consideration. Therefore, during periods of water scarcity, plans need to be put into place in order to provide the water required. These results demonstrate how SWAT can be used for irrigation planning and management.

xii.

# CHAPTER 7: Directions for further research

## 7.1 Drought monitoring and assessment

i. A drought monitoring network that involves multi-agency participation is key to decreasing Jamaica's vulnerability to drought. The current drought network is based solely on precipitation data, and does not incorporate any information from stream flow, or other parameters. It is important for the indices to be relevant across many spectrums, and so the comparison of the SPI to other hydrologic parameters such as streamflow, would also be highly beneficial.

ii. The SPI can also be used to monitor flood risk, and this is something that should be explored, especially in Jamaica where flooding has the potential to cause millions of dollars in damage.

iii. The use of the NDVI can be investigated for plantations, where the mosaic of brushland and agricultural land does not exist.

## 7.2 Irrigation planning

i. It would be extremely beneficial if irrigation demands were determined for future climate change scenarios. Planning needs to take place with future water demands in mind, as climate change will be one of the largest factors in determining what the available water supply will be.

ii. This research could be expanded in order to assess irrigation guidelines for other crops and soil types.

iii. Streamflow capacity for irrigation could be assessed in light of environmental, industrial and municipal demands, for future work with SWAT.

## 7.3 Hydrological modelling

i. In the future, the effects of increased urbanization will affect both availability and demand for water resources. This SWAT model can be used as a launch-pad for other studies investigating the repercussion of population increase.

ii. As karstic aquifers occupy almost 50% of the Island's area, the use of tools that can take into account the complex groundwater interactions that result from this karsticity should be explored. The use of artificial neural networks, as well as wavelet analysis, has the potential to significantly improve the performance of SWAT, especially in developing countries where the necessary data for input into SWAT are not available.

iii. Far more planning needs to take place in order to ensure that the data necessary for modelling is available. Increased access to climatic data and water quality data would make model results far more accurate, and a multi-agency approach should be taken to achieve this.

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# APPENDIX A: Irrigation Planning and Management

## A.1 Probability and Cumulative Distribution Functions

Let X denote the sample space of a random variable, and let *x* denote a possible value of X. The cumulative distribution function (CDF) of X, denoted as $F_x(x)$, is the probability that the random variable X is less than or equal to x:

$$F_x = P(X \leq x) = \sum_{x_i \leq x} P(x_i) \quad \text{A.1}$$

(Bedient and Huber, 2002; Stedinger et al., 1993)

Thus, F is the probability of non-exceedance of an event.

The probability density function (PDF), describes the relative likelihood that X takes on different values. It is the derivative of the cumulative distribution function, and is defined as follows:

$$f_x(x) = \frac{dF_X(x)}{dx} \quad \text{A.2}$$

(Stedinger et al., 1993)

<u>Gamma Distribution</u>

The Gamma distribution is used extensively in hydrology due to its well known mathematical properties and shape (Bedient and Huber, 2002). The PDF of the gamma function is as follows:

$$f_x(x) = |\beta|[\beta(x-\xi)]^{\alpha-1}\frac{exp[-\beta(x-\xi)]}{\Gamma(\alpha)} \quad \text{A.3}$$

Where $\Gamma$ is the Gamma function, $\beta$ is a scale parameter, and $\alpha$ is a shape parameter.

(Stedinger et al., 1993)

The Gamma distribution has the desirable properties of being bounded on the left, while having a positive skewness (Bedient and Huber, 2002; Stedinger et al., 1993).

Generalized Extreme Value Distribution

The Generalized Extreme Value (GEV) distribution is derived from three types of extreme value distributions developed by Gumbel (1958), and is most commonly used to describe the maximum of hydrologic processes, such as the maximum rainfall or flood discharge for the year (Stedinger et al., 1993). The cumulative distribution function of the GEV is given by:

$$F(x) = \begin{cases} exp\left\{-\left[1-\frac{c(x-a)}{b}\right]^{1/c}\right\} & c \neq 0 \\ exp\left\{-exp\left[-\frac{(x-a)}{b}\right]\right\} & c = 0 \end{cases} \qquad A.4$$

Where a, b and c are location, scale and shape parameters respectively.

(Chin, 2006)

Lognormal Distribution

Strictly positive random variables (X) have a lognormal distribution if the log of the random variables results in a normal distribution. In other words, the logarithm of the random variables is well described by a normal distribution (Bedient and Huber, 2002; Stedinger et al., 1993). This is particularly true in cases where the random variable results from a multiplicative process, and is the product of functions of several other variables. The CDF of the lognormal distribution is as follows:

$$F(x) = \frac{1}{x\sigma\sqrt{2\pi}} exp\left[-\frac{\left(lnx-\mu_y\right)^2}{2\sigma_y^2}\right], \quad x > 0 \qquad A.5$$

where $\mu_y$ and $\sigma_y^2$ are the mean and variance of Y, where Y = ln *X.*

**Table A.1: Monthly rainfall Values for Savanna-la-mar for different cumulative probabilities**

| Cumulative Probability | Exceedance Probability | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0.01 | 0.99 | 5 | 0 | 0 | 0 | 31 | 25 | 25 | 68 | 55 | 66 | 12 | 0 |
| 0.05 | 0.95 | 14 | 5 | 6 | 21 | 61 | 46 | 46 | 106 | 80 | 87 | 34 | 9 |
| 0.10 | 0.90 | 20 | 12 | 13 | 37 | 81 | 60 | 60 | 128 | 96 | 102 | 47 | 15 |
| 0.15 | 0.85 | 24 | 18 | 19 | 48 | 96 | 71 | 71 | 145 | 109 | 114 | 57 | 20 |
| 0.20 | 0.80 | 28 | 23 | 25 | 58 | 109 | 81 | 81 | 159 | 121 | 124 | 66 | 25 |
| 0.25 | 0.75 | 32 | 27 | 30 | 67 | 122 | 91 | 91 | 171 | 131 | 134 | 73 | 29 |
| 0.30 | 0.70 | 36 | 32 | 35 | 75 | 134 | 100 | 100 | 183 | 142 | 145 | 81 | 34 |
| 0.35 | 0.65 | 39 | 37 | 41 | 83 | 146 | 110 | 110 | 194 | 153 | 155 | 88 | 38 |
| 0.40 | 0.60 | 43 | 41 | 46 | 90 | 158 | 119 | 119 | 206 | 164 | 166 | 96 | 42 |
| 0.45 | 0.55 | 47 | 46 | 52 | 98 | 171 | 130 | 130 | 217 | 175 | 177 | 103 | 47 |
| 0.50 | 0.50 | 52 | 52 | 58 | 106 | 185 | 141 | 141 | 229 | 187 | 189 | 111 | 52 |
| 0.55 | 0.45 | 57 | 57 | 65 | 114 | 200 | 153 | 153 | 241 | 201 | 203 | 119 | 58 |
| 0.60 | 0.40 | 62 | 64 | 72 | 123 | 216 | 166 | 166 | 254 | 215 | 218 | 128 | 64 |
| 0.65 | 0.35 | 68 | 71 | 81 | 132 | 234 | 182 | 182 | 267 | 232 | 236 | 138 | 71 |
| 0.70 | 0.30 | 75 | 79 | 91 | 143 | 254 | 200 | 200 | 283 | 251 | 256 | 148 | 80 |
| 0.75 | 0.25 | 84 | 89 | 103 | 154 | 279 | 221 | 221 | 300 | 275 | 282 | 161 | 90 |
| 0.80 | 0.20 | 94 | 102 | 118 | 168 | 309 | 249 | 249 | 320 | 304 | 314 | 176 | 103 |
| 0.85 | 0.15 | 109 | 119 | 139 | 185 | 349 | 286 | 286 | 345 | 343 | 359 | 195 | 120 |
| 0.90 | 0.10 | 131 | 144 | 172 | 207 | 408 | 344 | 344 | 379 | 402 | 428 | 221 | 147 |
| 0.95 | 0.05 | 174 | 194 | 236 | 244 | 518 | 457 | 457 | 434 | 515 | 571 | 267 | 202 |
| 0.99 | 0.01 | 312 | 346 | 446 | 322 | 833 | 826 | 826 | 553 | 866 | 1063 | 379 | 382 |

**Table A.2: Monthly rainfall Values for Beckford Kraal for different cumulative probabilities**

| Cumulative Probability | Exceedance Probability | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0.01 | 0.99 | 4 | 0 | 2 | 11 | 8 | 0 | 7 | 18 | 71 | 97 | 25 | 0 |
| 0.05 | 0.95 | 11 | 1 | 11 | 24 | 41 | 11 | 22 | 43 | 84 | 120 | 39 | 9 |
| 0.10 | 0.90 | 16 | 9 | 18 | 35 | 64 | 19 | 31 | 59 | 93 | 136 | 48 | 16 |
| 0.15 | 0.85 | 19 | 14 | 23 | 44 | 81 | 26 | 39 | 71 | 100 | 149 | 55 | 21 |
| 0.20 | 0.80 | 23 | 19 | 28 | 53 | 97 | 33 | 45 | 81 | 108 | 160 | 62 | 26 |
| 0.25 | 0.75 | 26 | 23 | 33 | 61 | 112 | 39 | 52 | 91 | 115 | 170 | 69 | 30 |
| 0.30 | 0.70 | 29 | 27 | 37 | 69 | 126 | 46 | 58 | 101 | 122 | 181 | 75 | 35 |
| 0.35 | 0.65 | 32 | 31 | 42 | 78 | 141 | 53 | 64 | 110 | 130 | 192 | 82 | 39 |
| 0.40 | 0.60 | 35 | 35 | 47 | 86 | 157 | 61 | 71 | 120 | 138 | 203 | 89 | 44 |
| 0.45 | 0.55 | 39 | 39 | 53 | 95 | 173 | 69 | 77 | 130 | 148 | 215 | 96 | 48 |
| 0.50 | 0.50 | 43 | 44 | 59 | 104 | 190 | 79 | 84 | 140 | 158 | 227 | 104 | 54 |
| 0.55 | 0.45 | 47 | 48 | 65 | 114 | 209 | 90 | 92 | 151 | 169 | 241 | 113 | 59 |
| 0.60 | 0.40 | 51 | 53 | 73 | 124 | 230 | 102 | 100 | 163 | 183 | 256 | 123 | 65 |
| 0.65 | 0.35 | 56 | 58 | 82 | 136 | 254 | 118 | 110 | 176 | 199 | 274 | 135 | 73 |
| 0.70 | 0.30 | 62 | 64 | 92 | 149 | 282 | 136 | 121 | 192 | 219 | 294 | 148 | 81 |
| 0.75 | 0.25 | 70 | 70 | 105 | 164 | 316 | 161 | 134 | 209 | 244 | 319 | 165 | 91 |
| 0.80 | 0.20 | 79 | 78 | 122 | 181 | 359 | 194 | 151 | 231 | 278 | 351 | 187 | 104 |
| 0.85 | 0.15 | 92 | 88 | 145 | 203 | 417 | 243 | 173 | 260 | 329 | 394 | 217 | 121 |
| 0.90 | 0.10 | 111 | 102 | 183 | 233 | 506 | 327 | 206 | 301 | 415 | 461 | 265 | 147 |
| 0.95 | 0.05 | 149 | 125 | 262 | 283 | 682 | 527 | 269 | 376 | 616 | 594 | 365 | 199 |
| 0.99 | 0.01 | 272 | 181 | 558 | 392 | 1249 | 1484 | 459 | 579 | 1546 | 1031 | 721 | 367 |

**Table A.3: Monthly rainfall values for Serge Island for different cumulative probabilities**

| Cumulative Probability | Exceedance Probability | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0.01 | 0.99 | 1 | 0 | 0 | 0 | 0 | 6 | 25 | 20 | 7 | 17 | 11 | 0 |
| 0.05 | 0.95 | 11 | 5 | 4 | 3 | 20 | 21 | 46 | 45 | 38 | 54 | 29 | 13 |
| 0.10 | 0.90 | 17 | 11 | 9 | 10 | 41 | 36 | 61 | 66 | 59 | 78 | 46 | 23 |
| 0.15 | 0.85 | 23 | 15 | 14 | 16 | 58 | 50 | 72 | 83 | 75 | 98 | 62 | 30 |
| 0.20 | 0.80 | 27 | 19 | 18 | 21 | 74 | 65 | 81 | 99 | 90 | 115 | 76 | 37 |
| 0.25 | 0.75 | 32 | 23 | 22 | 26 | 89 | 79 | 90 | 114 | 104 | 131 | 90 | 43 |
| 0.30 | 0.70 | 37 | 27 | 26 | 31 | 103 | 94 | 99 | 130 | 118 | 147 | 105 | 50 |
| 0.35 | 0.65 | 41 | 31 | 30 | 36 | 118 | 109 | 108 | 145 | 133 | 163 | 120 | 56 |
| 0.40 | 0.60 | 46 | 35 | 34 | 41 | 134 | 125 | 117 | 161 | 148 | 180 | 135 | 63 |
| 0.45 | 0.55 | 51 | 40 | 39 | 47 | 150 | 143 | 126 | 177 | 163 | 198 | 151 | 70 |
| 0.50 | 0.50 | 57 | 44 | 44 | 53 | 168 | 161 | 136 | 194 | 180 | 216 | 168 | 78 |
| 0.55 | 0.45 | 63 | 50 | 49 | 60 | 187 | 181 | 147 | 212 | 199 | 237 | 186 | 86 |
| 0.60 | 0.40 | 69 | 56 | 55 | 68 | 209 | 203 | 159 | 232 | 220 | 259 | 206 | 96 |
| 0.65 | 0.35 | 77 | 62 | 63 | 77 | 234 | 228 | 172 | 253 | 244 | 285 | 228 | 107 |
| 0.70 | 0.30 | 86 | 71 | 71 | 88 | 264 | 256 | 187 | 277 | 272 | 315 | 253 | 119 |
| 0.75 | 0.25 | 97 | 80 | 81 | 102 | 299 | 288 | 205 | 305 | 306 | 350 | 282 | 135 |
| 0.80 | 0.20 | 112 | 93 | 95 | 120 | 345 | 328 | 228 | 337 | 349 | 396 | 317 | 155 |
| 0.85 | 0.15 | 131 | 111 | 114 | 145 | 409 | 378 | 258 | 378 | 408 | 456 | 360 | 182 |
| 0.90 | 0.10 | 162 | 139 | 144 | 186 | 507 | 447 | 302 | 434 | 500 | 549 | 420 | 224 |
| 0.95 | 0.05 | 223 | 196 | 206 | 273 | 705 | 564 | 385 | 526 | 684 | 728 | 520 | 308 |
| 0.99 | 0.01 | 433 | 397 | 432 | 605 | 1383 | 830 | 628 | 728 | 1303 | 1293 | 743 | 593 |

**Table A.4: Monthly Actual Evapotranspiration Values (mm)**

| Location | Etc | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Savanna-la-mar** | Vegetables | 76 | 121 | 140 | 129 | 88 | 127 | 135 | 121 | 75 | 115 | 106 | 106 |
| | Sugarcane | 89 | 71 | 46 | 44 | 152 | 145 | 155 | 148 | 126 | 126 | 116 | 70 |
| **Beckford Kraal** | Vegetables | 63 | 101 | 127 | 127 | 97 | 138 | 152 | 194 | 77 | 108 | 94 | 83 |
| | Sugarcane | 73 | 60 | 42 | 44 | 169 | 158 | 174 | 238 | 128 | 119 | 104 | 54 |
| **Serge Island** | Vegetables | 82 | 117 | 143 | 154 | 107 | 163 | 185 | 152 | 90 | 149 | 132 | 111 |
| | Sugarcane | 96 | 69 | 47 | 53 | 186 | 187 | 211 | 186 | 150 | 165 | 146 | 73 |

**Table A.5: Average monthly available soil moisture values (mm)**

| Location | January | February | March | April | May | June | July | August | September | October | November | December |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Savanna-la-mar | 68 | 52 | 39 | 46 | 95 | 98 | 106 | 138 | 143 | 153 | 135 | 92 |
| Beckford Kraal | 137 | 105 | 88 | 86 | 134 | 117 | 91 | 79 | 130 | 182 | 183 | 163 |
| Serge Island | 40 | 29 | 19 | 13 | 54 | 66 | 52 | 66 | 83 | 89 | 90 | 63 |

**Table A.6: Irrigation efficiencies for different application methods**

| Method of Irrigation | Irrigation Efficiency |
|---|---|
| Sprinkler | 0.75 |
| Surface | 0.45 |
| Localized (drip) | 0.9 |

Table A. 7: Irrigation values for Savanna-la-mar : vegetables and sugarcane

| Month | | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Vegetables | Irrigation Requirement (mm) | 0 | 59 | 90 | 52 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 3 |
| | Sprinkler Application (mm) | 0 | 79 | 119 | 69 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 3 |
| | Surface Application (mm) | 0 | 132 | 199 | 115 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 6 |
| | Localized (Drip) Application(mm) | 0 | 66 | 100 | 57 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 3 |
| Sugarcane | Irrigation Requirement (mm) | 0 | 17 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | Sprinkler Application (mm) | 0 | 22 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | Surface Application (mm) | 0 | 37 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | Localized (Drip) Application (mm) | 0 | 18 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

**Table A. 8: Irrigation values for Beckford Kraal: vegetables and sugarcane**

| Month | | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Vegetables** | Irrigation Requirement (mm) | 0 | 0 | 27 | 16 | 0 | 0 | 29 | 55 | 0 | 0 | 0 | 0 |
| | Sprinkler Application (mm) | 0 | 0 | 36 | 22 | 0 | 0 | 38 | 74 | 0 | 0 | 0 | 0 |
| | Surface Application (mm) | 0 | 0 | 60 | 36 | 0 | 0 | 64 | 123 | 0 | 0 | 0 | 0 |
| | Localized (Drip) Application(mm) | 0 | 0 | 30 | 18 | 0 | 0 | 32 | 61 | 0 | 0 | 0 | 0 |
| **Sugarcane** | Irrigation Requirement (mm) | 0 | 0 | 0 | 0 | 0 | 0 | 23 | 59 | 0 | 0 | 0 | 0 |
| | Sprinkler Application (mm) | 0 | 0 | 0 | 0 | 0 | 0 | 31 | 78 | 0 | 0 | 0 | 0 |
| | Surface Application (mm) | 0 | 0 | 0 | 0 | 0 | 0 | 51 | 131 | 0 | 0 | 0 | 0 |
| | Localized (Drip) Application (mm) | 0 | 0 | 0 | 0 | 0 | 0 | 26 | 65 | 0 | 0 | 0 | 0 |

**Table A.9: Irrigation values for Serge Island: vegetables and sugarcane**

| Month | | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Vegetables** | Irrigation Requirement (mm) | 30 | 80 | 118 | 133 | 4 | 48 | 69 | 16 | 0 | 0 | 0 | 32 |
| | Sprinkler Application (mm) | 40 | 107 | 157 | 178 | 6 | 64 | 92 | 21 | 0 | 0 | 0 | 42 |
| | Surface Application (mm) | 67 | 179 | 261 | 296 | 10 | 106 | 153 | 35 | 0 | 0 | 0 | 70 |
| | Localized (Drip) Application(mm) | 33 | 89 | 131 | 148 | 5 | 53 | 76 | 18 | 0 | 0 | 0 | 35 |
| **Sugarcane** | Irrigation Requirement (mm) | 27 | 39 | 23 | 34 | 50 | 45 | 66 | 23 | 0 | 0 | 0 | 1 |
| | Sprinkler Application (mm) | 37 | 52 | 31 | 45 | 67 | 60 | 87 | 31 | 0 | 0 | 0 | 1 |
| | Surface Application (mm) | 61 | 86 | 52 | 76 | 111 | 100 | 146 | 51 | 0 | 0 | 0 | 2 |
| | Localized (Drip) Application (mm) | 31 | 43 | 26 | 38 | 56 | 50 | 73 | 26 | 0 | 0 | 0 | 1 |

# APPENDIX B- Drought Indices Determination

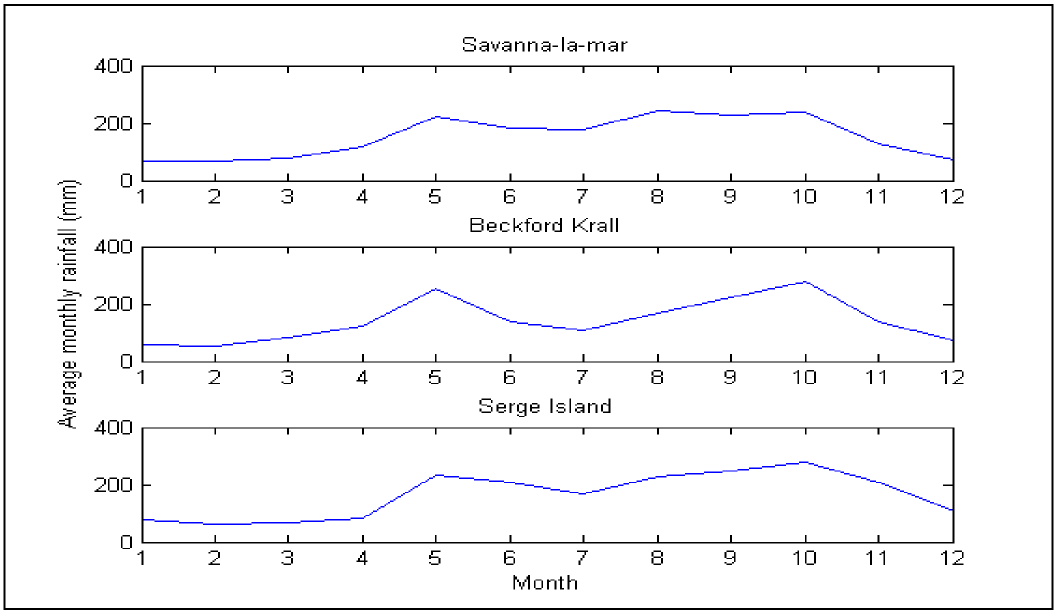


**Figure B.1: Monthly rainfall hydrographs for Savanna-la-mar, Beckford Kraal and Serge Island**

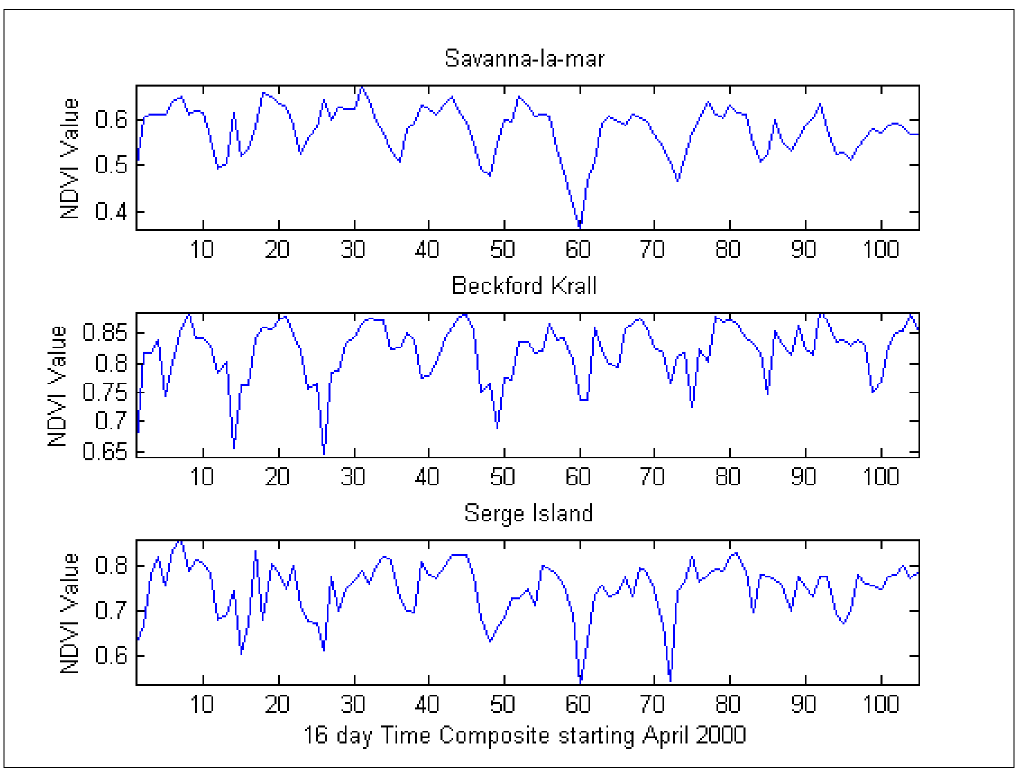


**Figure B.2: NDVI Time series for Savanna-la-mar, Beckford Kraal and Serge Island**

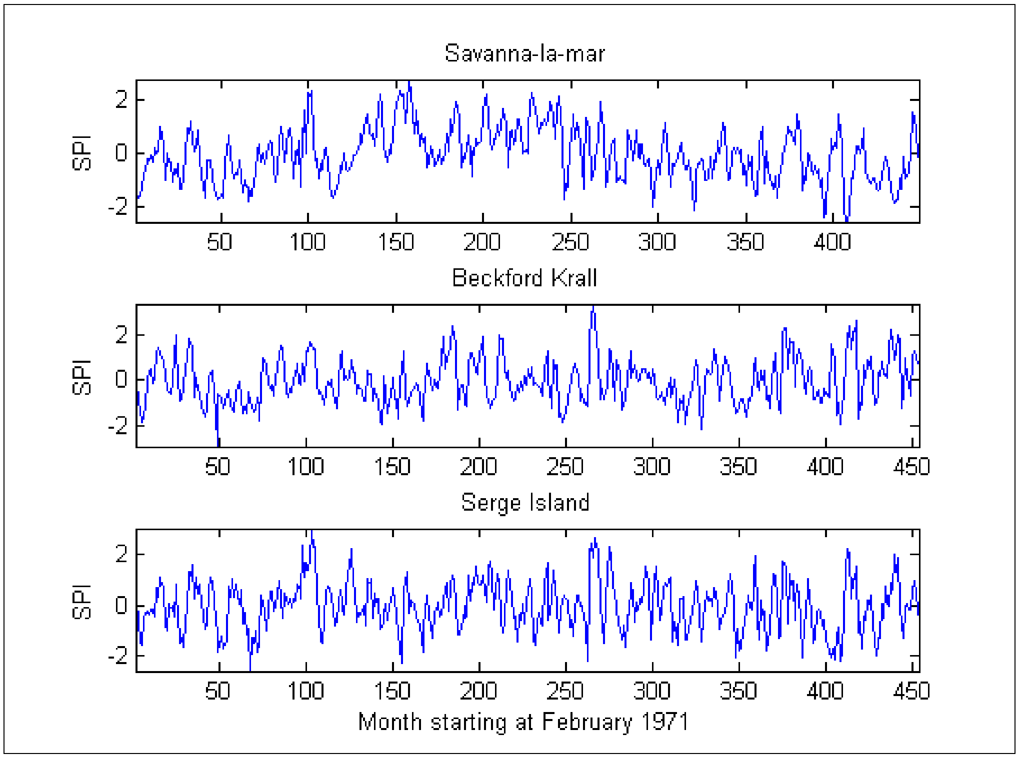


**Figure B.3: SPI time series for Savanna-la-mar, Beckford Kraal and Serge Island**

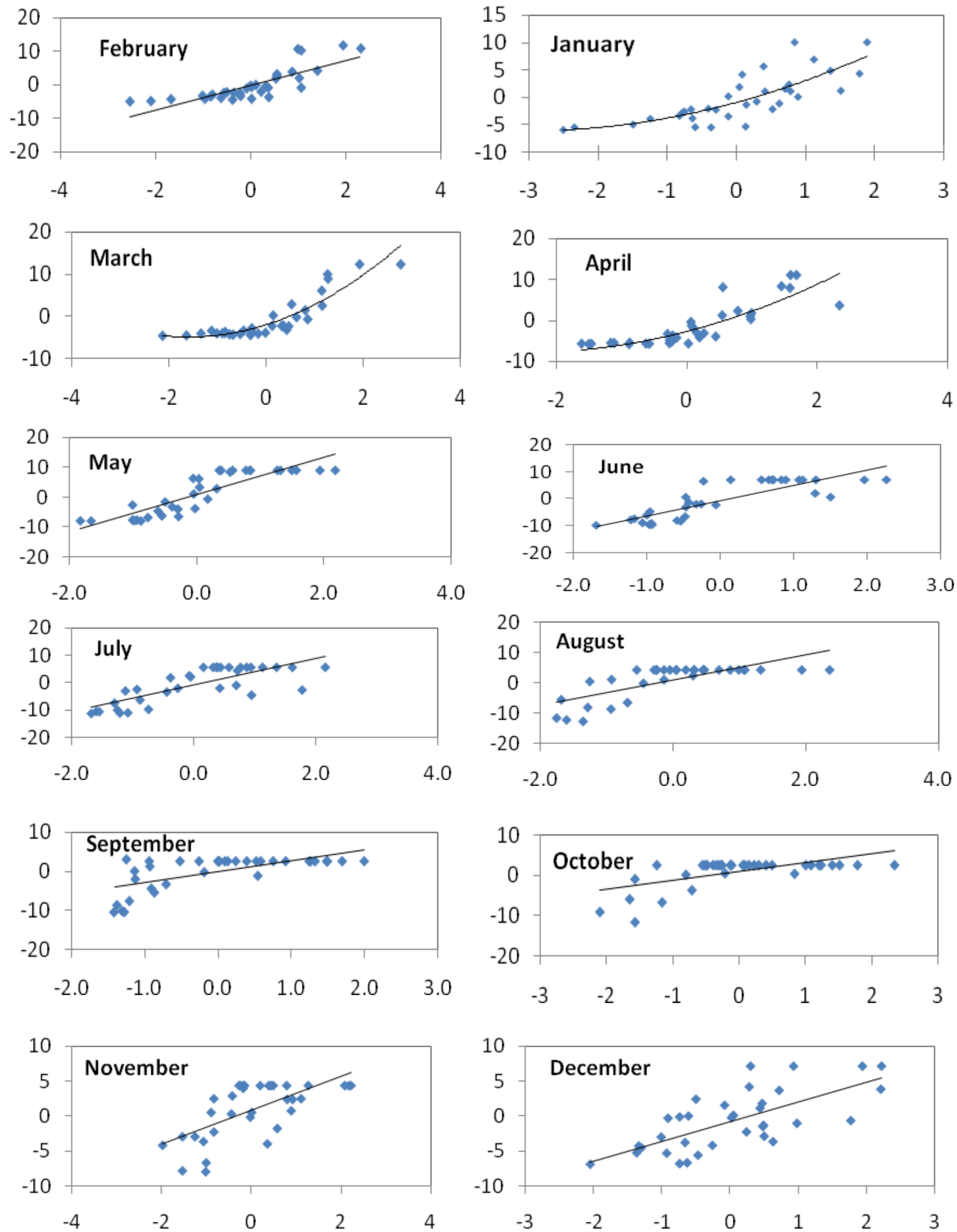


**Figure B.4: Scatter plots for Deseasonalized Soil moisture values vs. SPI values for Savanna-la-Mar. Note that all SPI values are 3 month SPI values except for January, which is 1 month**

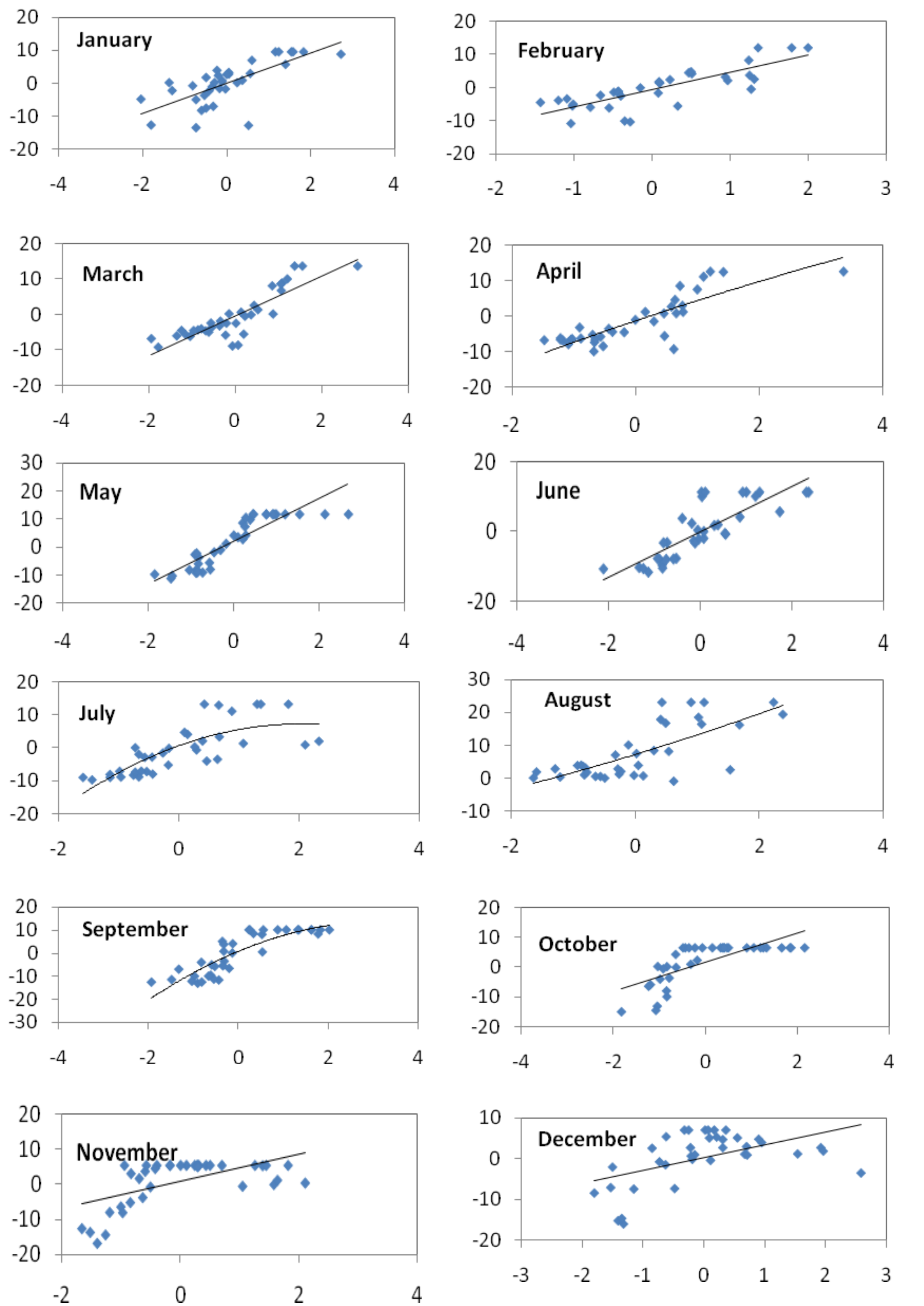


**Figure B.5: Scatter plots for Deseasonalized Soil moisture values vs. SPI values for Beckford Kraal. Note that all SPI values are 3 month SPI values except for January, which is 1 month**

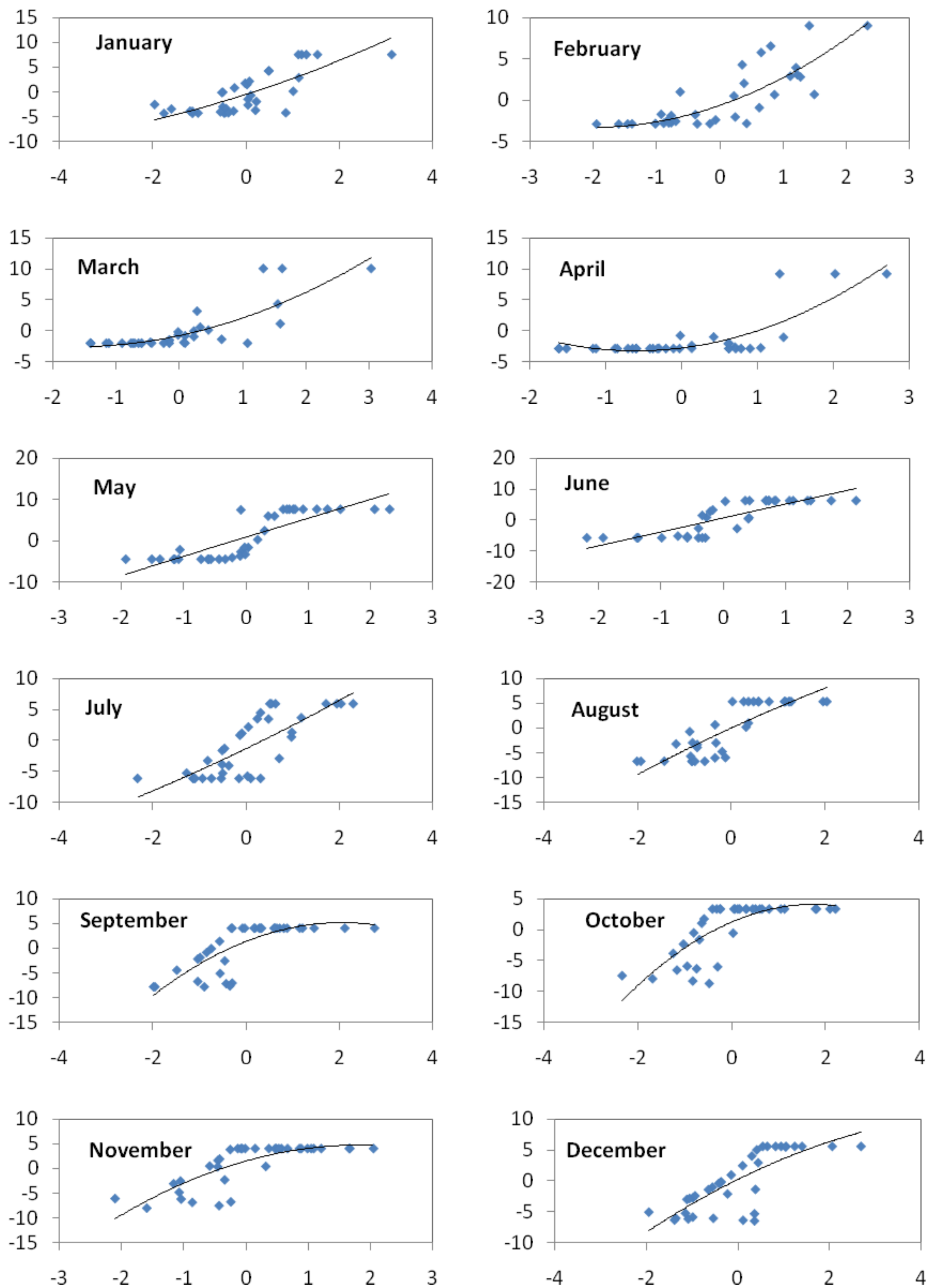


**Figure B.6: Scatter plots for deseasonalized soil moisture values vs. SPI values for Serge Island. Note that all SPI values are 1 month SPI values**

**Table B.1: Values of available soil moisture for various classifications of positive SPI values (Savanna-la-Mar)**

| Water Availability | 3 month SPI values | Feb | Mar | Apr | May | Jun |
|---|---|---|---|---|---|---|
| Near normal | -0.5 | 3.3 | 1.1 | 1.5 | 5.8 | 6.6 |
| | 0.5 | 7.0 | 4.7 | 5.6 | 12.1 | 12.2 |
| Abnormally moist | 0.51 | 7.1 | 4.7 | 5.7 | 12.2 | 12.3 |
| | 0.79 | 8.1 | 6.2 | 7.1 | 13.9 | 13.9 |
| Moderately moist | 0.8 | 8.1 | 6.2 | 7.2 | 14.0 | 13.9 |
| | 1.29 | 10.0 | 9.1 | 10.0 | 17.0 | 16.7 |
| Very moist | 1.3 | 10.0 | 9.2 | 10.1 | FC | 16.8 |
| | 1.59 | 11.1 | 11.2 | 12.0 | FC | FC |
| Extremely moist | 1.6 | 11.1 | 11.2 | 12.0 | FC | FC |
| | 1.99 | 12.6 | 14.2 | 14.8 | FC | FC |
| Exceptionally moist | 2 | 12.6 | 14.3 | 14.9 | FC | FC |

**FC= Field Capacity**

**Table B.2: Values of available soil moisture for various classifications of positive SPI values (Beckford Kraal)**

| Water Availability | 3 month SPI Value | Feb | Mar | Apr | May | Jun | Sep |
|---|---|---|---|---|---|---|---|
| Near normal | -0.5 | 7.7 | 6.1 | 6.0 | 9.7 | 8.4 | 9.0 |
| | 0.5 | 12.9 | 11.8 | 11.7 | 17.3 | 14.9 | 16.5 |
| Abnormally moist | 0.51 | 12.9 | 11.9 | 11.8 | 17.3 | 15.0 | 16.6 |
| | 0.79 | 14.4 | 13.4 | 13.4 | 19.5 | 16.8 | 18.7 |
| Moderately moist | 0.8 | 14.5 | 13.5 | 13.4 | 19.5 | 16.9 | 18.8 |
| | 1.29 | 17.0 | 16.3 | 16.2 | FC | 20.1 | 22.5 |
| Very moist | 1.3 | 17.1 | 16.3 | 16.3 | FC | 20.1 | 22.5 |
| | 1.59 | 18.6 | 18.0 | 17.9 | FC | 22.0 | FC |
| Extremely moist | 1.6 | 18.6 | 18.0 | 18.0 | FC | 22.1 | FC |
| | 1.99 | 20.7 | 20.2 | 20.2 | FC | FC | FC |
| Exceptionally moist | 2 | 20.7 | 20.3 | 20.2 | FC | FC | FC |

**FC= Field Capacity**

**Table B.3: Values of available soil moisture for various classifications of positive SPI values (Serge Island)**

| Water Availability | SPI category | 1 month SPI Value | Feb | Mar | Apr |
|---|---|---|---|---|---|
| Near normal | -0.5 to + 0.5 | 0.5 | 3.8 | 2.5 | 8.8 |
| | | -0.5 | 1.2 | 0.3 | 4.5 |
| Abnormally moist | 0.51 to 0.79 | -0.51 | 1.1 | 0.3 | 4.4 |
| | | 0.79 | 4.9 | 3.4 | 10.0 |
| Moderately moist | 0.80 to 1.29 | 0.8 | 4.9 | 3.4 | 10.0 |
| | | 1.29 | 6.9 | 5.1 | 12.0 |
| Very moist | 1.30 to 1.59 | 1.3 | 7.0 | 5.1 | 12.0 |
| | | 1.59 | 8.3 | 6.3 | FC |
| Extremely moist | 1.60 to 1.99 | 1.6 | 8.3 | 6.4 | FC |
| | | 1.99 | 10.3 | 8.1 | FC |
| Exceptionally moist | 2.00 and above | 2 | 10.4 | 8.1 | FC |

**FC= Field Capacity**

# APPENDIX C- SWAT Model Evaluation

**C.1: Available soil and landuse data**

Many of the parameters required by SWAT had not been measured for either the soils or the various land uses. This section outlines the relevant data which was available for both soil and land use. All the data was obtained from the Rural Physical Planning Unit of the Jamaica Ministry of Agriculture, unless otherwise indicated. The available soils data was:

- Textural information (clay, sand, silt)
- Depth of root limiting layer
- Qualitative description of internal drainage (rapid, slow)
- Hydrologic group
- Special management problems
- Soil layer depths
- Particle size distribution of each layer
- USLE Erosivity K factor (obtained from Evelyn, 2007)

The available land use data consisted of the curve numbers for Antecedent Moisture Condition (AMC) II for each of the hydrologic soil groups. These values were obtained from Evelyn (2007).

**C.2 : Model evaluation parameters**

General performance ratings were compiled for the RSR, NSE and PBIAS for calibration on a monthly basis by Moriasi et al. (2007), for steamflow, sediment and agricultural water quality indicators (nitrogen and phosphorus). The ratings for streamflow are shown in Table B.1, adapted from Moriasi et al. (2007).

**Table C.1: Performance ratings for Hydrologic Models (Moriasi et al., 2007)**

| **Performance Rating** | RSR | NSE | PBIAS |
|---|---|---|---|
| Very good | 0.00 ≤ RSR ≤ 0.50 | 0.75 ≤ NSE ≤ 1.00 | PBIAS < ± 10 |
| Good | 0.50 < RSR ≤ 0.60 | 0.65 ≤ NSE ≤ 0.75 | ± 10 ≤ PBIAS ≤ ± 15 |
| Satisfactory | 0.60 < RSR ≤ 0.70 | 0.50 ≤ NSE ≤ 0.65 | ± 15 ≤ PBIAS ≤ ± 25 |
| Unsatisfactory | RSR > 0.70 | NSE ≤ 0.50 | PBIAS ≥ ± 25 |

The Nash- Sutcliffe Efficiency Coefficient is calculated as follows:

$$\text{NSE} = 1 - \left[\frac{\sum_{i=1}(Y_i^{obs} - Y_i^{sim})^2}{\sum_{i=1}(Y_i^{obs} - Y^{mean})^2}\right]$$

Where is the *i*th observation for the constituent being evaluated, $^{a}$ is the mean of observed data for the constituent being evaluated, is the *i*th simulated value for the constituent being evaluated, and n is the total number of observations.

The Percent Bias index is calculated as follows:

$$\text{PBIAS} = \left[\frac{\sum_{i=1}(Y_i^{obs} - Y_i^{sim}) * 100}{\sum_{=1}(Y_i^{obs})}\right]$$

Where all parameters are as defined previously.

Lastly, the Root Mean Square Error (RSME)-observations standard deviation ratio (RSR) is calculated as follows:

$$\text{RSR} = \frac{}{TDEV} = \frac{\left[\sqrt{\sum_{i=1}(Y_i^{obs} - Y_i^{sim})^2}\right]}{\left[\sqrt{\sum_{=1}(Y_i^{obs} - Y_i^{mean})^2}\right]}$$

Where all parameters are as defined previously (Moriasi et al., 2007).

**C.3: Full description of model parameters used in SWAT**

The following tables describe the model parameters that were used in SWAT. It is hoped that these parameters can be used again in future modelling, in order to facilitate the increased use of hydrologic modelling with the island.

Table C.2: Land use parameters used to model the Rio Nuevo Watershed, St. Mary, Jamaica

| SWAT Parameter | Value | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| CROP NAME | Fields (FIDS) | Disturbed Broadleaf and Fields (DBFD) | Disturbed Broadleaf (DSBL) | Bamboo Disturbed Broadleaf (BBDB) | Bamboo and Fields | Fields Disturbed Broadleaf (FDDB) | Hot Peppers (HTPR) | Bananas (BANA) |
| BIO_E | 39 | 15 | 15 | 15 | 15 | 39 | 30 | 30 |
| HVSTI | 0.5 | 0.76 | 0.76 | 0.76 | 0.76 | 0.5 | 0.6 | 0.44 |
| BLAI | 3 | 5 | 5 | 5 | 5 | 3 | 2 | 4.5 |
| FRGRW1 | 0.15 | 0.05 | 0.05 | 0.05 | 0.05 | 0.15 | 0.15 | 0.05 |
| LAIMX1 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 |
| FRGRW2 | 0.5 | 0.40 | 0.4 | 0.4 | 0.4 | 0.5 | 0.5 | 0.4 |
| LAIMX2 | 0.95 | 0.95 | 0.95 | 0.95 | 0.95 | 0.95 | 0.95 | 0.95 |
| DLAI | 0.7 | 0.99 | 0.99 | 0.99 | 0.99 | 0.7 | 0.6 | 0.99 |
| CHTMX | 2.5 | 6 | 6 | 6 | 6 | 2.5 | 0.5 | 7.5 |
| RDMX | 2 | 3 | 3 | 3 | 3 | 2 | 0.45 | 3.5 |
| T_OPT | 25 | 30 | 30 | 30 | 30 | 25 | 30 | 30 |
| T_BASE | 8 | 10 | 10 | 10 | 10 | 8 | 18 | 10 |
| CNYLD | 0.014 | 0.0015 | 0.0015 | 0.0015 | 0.0015 | 0.014 | 0.0188 | 0.0064 |
| CPYLD | 0.0016 | 0.0003 | 0.0003 | 0.0003 | 0.0003 | 0.0016 | 0.003 | 0.0008 |
| BN1 | 0.047 | 0.006 | 0.006 | 0.006 | 0.006 | 0.047 | 0.06 | 0.06 |
| BN2 | 0.0177 | 0.002 | 0.002 | 0.002 | 0.002 | 0.0177 | 0.035 | 0.032 |
| BN3 | 0.0138 | 0.0015 | 0.0015 | 0.0015 | 0.0015 | 0.0138 | 0.025 | 0.016 |
| BP1 | 0.0048 | 0.0007 | 0.0007 | 0.0007 | 0.0007 | 0.0048 | 0.0053 | 0.003 |
| BP2 | 0.0018 | 0.0004 | 0.0004 | 0.0004 | 0.0004 | 0.0018 | 0.002 | 0.002 |
| BP3 | 0.0014 | 0.0003 | 0.0003 | 0.0003 | 0.0003 | 0.0014 | 0.0012 | 0.001 |
| WSYF | 0.3 | 0.01 | 0.01 | 0.01 | 0.01 | 0.3 | 0.25 | 0.01 |
| USLE_C | 0.2 | 0.001 | 0.001 | 0.001 | 0.001 | 0.2 | 0.03 | 0.001 |
| GSI | 0.007 | 0.002 | 0.002 | 0.002 | 0.002 | 0.007 | 0.005 | 0.0036 |
| VPDFR | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 |
| FRGMAX | 0.75 | 0.75 | 0.75 | 0.75 | 0.75 | 0.75 | 0.75 | 0.75 |
| WAVP | 7.2 | 8 | 8 | 8 | 8 | 7.2 | 8 | 8 |
| CO2HI | 660 | 660 | 660 | 660 | 660 | 660 | 660 | 660 |

| SWAT Parameter | Value | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **CROP NAME** | **Fields (FIDS)** | **Disturbed Broadleaf and Fields (DBFD)** | **Disturbed Broadleaf (DSBL)** | **Bamboo Disturbed Broadleaf (BBDB)** | **Bamboo and Fields** | **Fields Disturbed Broadleaf (FDDB)** | **Hot Peppers (HTPR)** | **Bananas (BANA)** |
| BIOEHI | 45 | 16 | 16 | 16 | 16 | 45 | 39 | 31 |
| RSDCO_PL | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 |
| OV_N | 0.14 | 0.1 | 0.1 | 0.1 | 0.1 | 0.14 | 0.14 | 0.14 |
| CN2A | 34 | 45 | 36 | 37 | 36 | 67 | 67 | 67 |
| CN2B | 78 | 66 | 60 | 61 | 60 | 78 | 77 | 78 |
| CN2C | 86 | 77 | 73 | 74 | 73 | 85 | 83 | 85 |
| CN2D | 90 | 83 | 79 | 80 | 79 | 89 | 87 | 89 |
| FERTFIELD | 1 | 0 | 0 | 0 | 0 | 1 | 1 | 1 |
| ALAI_MIN | 0 | 0.75 | 0.75 | 0.75 | 0.75 | 0 | 0 | 1.75 |
| BIO_LEAF | 0 | 0.3 | 0.3 | 0.3 | 0.3 | 0 | 0 | 0.3 |
| MAT_YRS | 0 | 10 | 10 | 10 | 10 | 0 | 0 | 10 |
| BMX_TREES | 0 | 1000 | 1000 | 1000 | 1000 | 0 | 0 | 200 |
| EXT_COEF | 0.65 | 0.65 | 0.65 | 0.65 | 0.65 | 0.65 | 0.65 | 0.45 |
| BM_DIEOFF | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 |

**Table C.3: Soil parameters used to model the Rio Nuevo sub-basin, St. Mary, Jamaica**

| SWAT Parameter | Value | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Soil name | DONNINGTON | STANN | KILLANCHOLLY | CARRON | UNION | BELFIELD | NONSUCH | WAITABIT | BUNDO | BONNYGATE |
| NLAYERS | 2 | 2 | 2 | 2 | 2 | 5 | 3 | 2 | 2 | 2 |
| HYDGRP | A | A | B | B | C | C | B | B | B | A |
| SOL_ZMX | 800 | 1600 | 304.8 | 600 | 1800 | 1778 | 1828.8 | 1500 | 304.8 | 250 |
| ANION_EXCL | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 |
| SOL_CRK | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 |
| SOL_Z1 | 300 | 250 | 150 | 300 | 220 | 203.2 | 177.8 | 320 | 177.8 | 80 |
| SOL_BD1 | 1.19 | 1.19 | 1.4 | 1.4 | 1.33 | 1.33 | 1.4 | 1.4 | 1.4 | 1.19 |
| SOL_AWC1 | 0.1 | 0.1 | 0.15 | 0.15 | 0.19 | 0.19 | 0.15 | 0.15 | 0.15 | 0.1 |
| SOL_K1 | 28 | 28 | 18 | 18 | 28 | 18 | 18 | 18 | 18 | 28 |
| SOL_CBN1 | 2 | 2 | 2 | 2 | 2 | 1.45 | 0.73 | 2 | 2 | 2 |
| CLAY1 | 29 | 45 | 60 | 48 | 53 | 22.5 | 38.5 | 58 | 60 | 55 |
| SILT1 | 45 | 54 | 20 | 34 | 38 | 52.72 | 54.15 | 17 | 20 | 29 |
| SAND1 | 26 | 1 | 20 | 18 | 9 | 24.78 | 7.35 | 25 | 20 | 16 |
| ROCK1 | 30 | 30 | 4.06 | 4.06 | 30 | 1.38 | 4.06 | 4.06 | 4.06 | 30 |
| SOL_ALB1 | 0.01 | 0.01 | 0.06 | 0.06 | 0.01 | 0.01 | 0.06 | 0.06 | 0.06 | 0.01 |
| USLE_K1 | 0.11 | 0.21 | 0.2 | 0.24 | 0.33 | 0.12 | 0.013 | 0.2 | 0.1 | 0.12 |
| SOL_EC1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| SOL_Z2 | 500 | 1350 | 154.8 | 300 | 1580 | 609.6 | 508 | 1180 | 508 | 170 |
| SOL_BD2 | 1.64 | 1.64 | 1.38 | 1.38 | 1.37 | 1.37 | 1.38 | 1.38 | 1.38 | 1.61 |
| SOL_AWC2 | 0.05 | 0.05 | 0.17 | 0.17 | 0.17 | 0.17 | 0.17 | 0.17 | 0.17 | 0.05 |

| SWAT Parameter | Value | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Soil name | DONNINGTON | ST. ANN | KILLANCHOLLY | CARRON | UNION | BELFIELD | NONSUCH | WAITABIT | BUNDO | BONNYGATE |
| SOL_K2 | 600 | 600 | 1.4 | 1.4 | 20 | 3.8 | 1.4 | 1.4 | 1.4 | 650 |
| SOL_CBN2 | 1.26 | 2 | 2 | 2 | 2 | 0.73 | 0.24 | 2 | 2 | 2 |
| CLAY2 | 25 | 64 | 60 | 62 | 71 | 60 | 38.5 | 60 | 60 | 63 |
| SILT2 | 45 | 35 | 20 | 32 | 21 | 20 | 54.15 | 17 | 20 | 27 |
| SAND2 | 30 | 1 | 20 | 6 | 8 | 20 | 7.35 | 23 | 20 | 10 |
| ROCK2 | 20 | 20 | 3.44 | 3.44 | 30 | 1.34 | 3.44 | 0 | 3.44 | 20 |
| SOL_ALB2 | 0.02 | 0.02 | 0.14 | 0.14 | 0.06 | 0.06 | 0.14 | 0.14 | 0.14 | 0.02 |
| USLE_K2 | 0.11 | 0.38 | 0.2 | 0.17 | 0.58 | 0.12 | 0.1 | 0.18 | 0.1 | 0.12 |
| SOL_EC2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| SOL_Z3 | 0 | 550 | 0 | 146.4 | 500 | 863.6 | 1828.8 | 550 | 1828.8 | 0 |
| SOL_BD3 | 0 | 1.19 | 0 | 1.35 | 1.37 | 1.56 | 1.35 | 1.3 | 1.35 | 0 |
| SOL_AWC3 | 0 | 0.05 | 0 | 0.16 | 0.17 | 0.12 | 0.16 | 0.09 | 0.16 | 0 |
| SOL_K3 | 0 | 28 | 0 | 3.8 | 5 | 3.8 | 3.8 | 0.07 | 3.8 | 0 |
| SOL_CBN3 | 0 | 0.08 | 0 | 0.08 | 0.58 | 0.58 | 0.08 | 0.44 | 0.08 | 0 |
| CLAY3 | 0 | 63 | 0 | 60 | 88 | 60 | 38.5 | 74 | 60 | 0 |
| SILT3 | 0 | 36 | 0 | 20 | 7 | 20 | 54.15 | 17 | 20 | 0 |
| SAND3 | 0 | 1 | 0 | 20 | 5 | 20 | 7.35 | 9 | 20 | 0 |
| ROCK3 | 0 | 20 | 0 | 3.38 | 20 | 1.38 | 3.38 | 0 | 3.38 | 0 |
| SOL_ALB3 | 0 | 0.01 | 0 | 0.2 | 0.08 | 0.08 | 0.2 | 0.1 | 0.2 | 0 |
| USLE_K3 | 0 | 0.14 | 0 | 0.24 | 0.08 | 0.12 | 0.24 | 0.23 | 0.24 | 0 |

| SWAT Parameter | Value | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Soil name | DONNINGTON | ST. ANN | KILLANCHOLLY | CARRON | UNION | BELFIELD | NONSUCH | WAITABIT | BUNDO | BONNYGATE |
| SOL_EC3 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| SOL_Z4 | 0 | 500 | 0 | 0 | 400 | 1473.2 | 0 | 400 | 0 | 0 |
| SOL_BD4 | 0 | 1.64 | 0 | 0 | 1.56 | 1.51 | 0 | 1.35 | 0 | 0 |
| SOL_AWC4 | 0 | 0.05 | 0 | 0 | 0.12 | 0.15 | 0 | 0.16 | 0 | 0 |
| SOL_K4 | 0 | 600 | 0 | 0 | 18 | 7 | 0 | 3.8 | 0 | 0 |
| SOL_CBN4 | 0 | 0.08 | 0 | 0 | 2 | 0.58 | 0 | 0.08 | 0 | 0 |
| CLAY4 | 0 | 72 | 0 | 0 | 92 | 27.5 | 0 | 78 | 0 | 0 |
| SILT4 | 0 | 27 | 0 | 0 | 4 | 37.82 | 0 | 18 | 0 | 0 |
| SAND4 | 0 | 1 | 0 | 0 | 4 | 34.68 | 0 | 4 | 0 | 0 |
| ROCK4 | 0 | 20 | 0 | 0 | 1.38 | 7.02 | 0 | 3.38 | 0 | 0 |
| SOL_ALB4 | 0 | 0.02 | 0 | 0 | 0.08 | 0.08 | 0 | 0.2 | 0 | 0 |
| USLE_K4 | 0 | 0.08 | 0 | 0 | 0.08 | 0.12 | 0 | 0.24 | 0 | 0 |
| SOL_EC4 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| SOL_Z5 | 0 | 0 | 0 | 0 | 200 | 1778 | 0 | 0 | 0 | 0 |
| SOL_BD5 | 0 | 0 | 0 | 0 | 1.56 | 1.79 | 0 | 0 | 0 | 0 |
| SOL_AWC5 | 0 | 0 | 0 | 0 | 0.12 | 0.1 | 0 | 0 | 0 | 0 |
| SOL_K5 | 0 | 0 | 0 | 0 | 18 | 500 | 0 | 0 | 0 | 0 |
| SOL_CBN5 | 0 | 0 | 0 | 0 | 2 | 0.19 | 0 | 0 | 0 | 0 |
| CLAY5 | 0 | 0 | 0 | 0 | 93 | 15 | 0 | 0 | 0 | 0 |

| SWAT Parameter | **Value** | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Soil name | DONNINGTON | STANN | KILLANCHOLLY | CARRON | UNION | BELFIELD | NONSUCH | WAITABIT | BUNDO | BONNYGATE |
| SILT5 | 0 | 0 | 0 | 0 | 4 | 30 | 0 | 0 | 0 | 0 |
| SAND5 | 0 | 0 | 0 | 0 | 3 | 55 | 0 | 0 | 0 | 0 |
| ROCK5 | 0 | 0 | 0 | 0 | 1.38 | 20 | 0 | 0 | 0 | 0 |
| SOL_ALB5 | 0 | 0 | 0 | 0 | 0.08 | 0.16 | 0 | 0 | 0 | 0 |
| USLE_K5 | 0 | 0 | 0 | 0 | 0.09 | 0 | 0 | 0 | 0 | 0 |
| SOL_EC5 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |