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The development of the SPI and NDVI for 3 study sites in Jamaica, with an investigation into their use in understanding soil water during water stressed conditions in Jamaica

Johanna Richards[1], Dr. Chandra Madramootoo[2], Adrian Trotman[3]

[1] Department of Bioresource Engineering, McGill University, 21,111 Lakeshore Road, Ste. Anne de Bellevue, QC, Canada, H9X 3V9 ; E-mail: johanna.richards@mail.mcgill.ca
[2] Department of Bioresource Engineering, McGill University, 21,111 Lakeshore Road, Ste. Anne de Bellevue, QC, Canada, H9X 3V9; E-mail: chandra.madramootoo@mcgill.ca
[3] Caribbean Institute of Meteorology and Hydrology, Husbands, St. James BB23006, Barbados; E-mail: atrotman@cimh.edu.bb

ABSTRACT

Agricultural production is an important contributor to the Jamaican economy. However drought has the potential to cause millions of dollars in crop losses. In fact, there were crop losses amounting to six million USD in the 1999/2000 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 paper 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 water. Depending on location, either the one or three month SPI was found to be more representative of soil water 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 paper provides soil water values for different categories/values of the SPI, as well as the NDVI, for use in future drought management within the island.

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

1.0 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)

Rainfall is the most variable climatic parameter in the Island. The 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 890 mm annually (Meteorological Service of Jamaica, 2009). The rainfall pattern throughout most of the island is bi-modal, with two wet seasons per year. These seasons typically occur from May to June, and from September to November (Meteorological Service of

Jamaica, 2009). December to March is typically the period with the least rainfall. Water shortages during this dry season can cause difficult problems, especially in light of the fact that this period corresponds to the boreal winter season, which is the peak tourist season in Jamaica. The heavy influx of tourists can cause an even greater strain on local water supplies, exacerbating the problems that residents face when dealing with water stress (Trotman et al., 2009).

The Jamaican agricultural sector employs approximately 20% of the labour force (FAO, 2003; PIOJ, 2008). The main exports are sugar, bananas, citrus, coffee, cocoa and coconuts (MOA, 2007). Despite the significant labour force involved in agriculture, this sector accounts for only approximately 6% of Jamaica's Gross Domestic Product (GDP) (FAO, 2010). The sector has been threatened recently by globalization, as well as a changing climate (Ricketts, 2005). It has also been threatened by increasing importations, especially from the U.S. where agricultural subsidies result in the majority of imported food products being cheaper than locally grown products (Weis, 2004).

Agriculture is heavily dependent on rainfall, and, approximately 10% of Jamaica's 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. In fact, some estimates indicate that as much as 95% of all domestic agricultural production is rain-fed (Chen et al., 2005).In light of this, the need for irrigation planning and expansion has been acknowledged by government agencies and researchers alike (NIC, 2009).

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 Nino/ 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 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). In fact, 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 representing no vegetation. Negative values represent non-vegetative surfaces, while values approaching 1 represent very dense vegetation (Anyamba et al., 2005).

In general, in the West Indies, more complex and comprehensive indices such as the SPI, as well as the Palmer 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 Standard Precipitation Index (SPI) and Normalized Difference Vegetation Index (NDVI) for the Caribbean, and to relate these to hydrologic parameters such as soil water and streamflow.

2.0 Materials and methods

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 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.

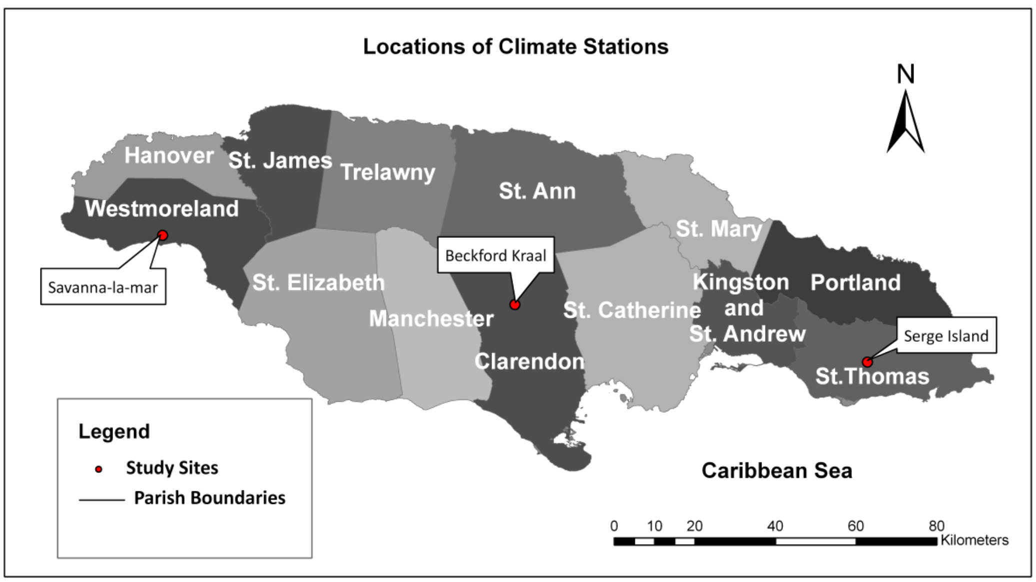

Figure 1: Location of climate stations

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.

2.2 Determination of soil water

A conceptual soil water model based on the water balance, was used for this research (Chin, 2006). The soil water 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:

(1)

—, provided that ′ (2)

L_s is the moisture loss from the surface layer, ′ is the available moisture in the surface layer at the start of the month, is potential evapotranspiration, P is monthly precipitation, is the moisture loss from the underlying soil, ′ is the available moisture stored in the underlying soil at the start of the month, and 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 water, 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 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 1, and hence all values of available soil water listed in

Table 1: Soil water parameters

Study Site	Field Capacity ′ (cm)	Wilting Point (cm)	Available Water Capacity (cm)
Savanna-la-Mar	31	14	17
Beckford Kraal	44	21	23
Serge Island	21	9	12

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.

2.3 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 Normalized NDVI for Jamaica was obtained from 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.

2.4 Seasonality analysis of the soil water 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 water, 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 water.

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 9 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 16 day time period. This seasonal value was then subtracted from the raw 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 water, the difference being that each 'season' was the month. The process is described as follows, and was modified from Weissling and Xie (2009):

(3)

(4)

Where TS_{ds} is the sixteen day deseasonalized mean in the NDVI time series (or the monthly deseasonalized mean in the soil water time series), TS_{raw} is the sixteen-day raw 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.

2.5 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 dryer 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 water, the one and three month SPI for each month was correlated to the concurrent monthly soil water. 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 water for March 1971. Like the NDVI, attempts were also made to lag the soil water by one and two months in order to see if the correlation results would improve.

2.6 Correlation and regression analysis

A bivariate correlation and regression analysis was carried out between monthly NDVI and soil water 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). Cross-correlation (lag) analysis was carried out for the NDVI and soil water time series, by lagging the NDVI for a month and two months. It is important to understand the NDVI was compared to soil water on a monthly basis, in other words, not as a continuous time series. This was done as the relationship between vegetation and soil water can change from month to month (Wang et al., 2007). The SPI and available soil water were also compared on a month-by-month basis, as the relationship between precipitation (and thus SPI) and soil water is different for each month. In general, in wetter months, small precipitation events can lead to the soil reaching field capacity. In dryer months however, much larger precipitation events would be needed in order for the soil to reach field capacity.

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

(5)

These relationships were then used in order to determine soil water 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.

3.0 Results

3.1 The relationship between NDVI and soil water

As mentioned previously, the NDVI and soil water were compared on a month-by-month basis. As a result of the correlation analysis, it was found that the NDVI has a good relationship with soil water 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 values for each of these months are shown in Table 2. All values are reported within a 5% level of significance.

Table 2: R^2 regression coefficients for NDVI and available soil water 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

3.2 The relationship between SPI and available soil water

On the other hand, the three month SPI showed reasonable R^2 regressions (≥ 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 3). All values are reported within a 5% level of significance. Table 3 shows the R^2 coefficients for each month. The coefficients for the three month SPI values and available soil water are reported for Savanna-la-mar and Beckford Kraal, unless otherwise indicated. The coefficients for the one month SPI and available soil water are shown for Serge Island.

Table 3: R^2 regression coefficients for SPI and soil water

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 these are the ones listed in the table.

The correlations shown in Table 3 highlight the months for which relationships between the SPI and available soil water can be derived through use of a curve of best fit. Tables 4 to 7 show actual values of soil water based on the categories of the SPI derived by the NOAA NCDC, for each location, and for each relevant month, for negative values of the SPI (WP in these tables refer to wilting point). 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 water.

Table 4: Raw available soil water values for the SPI categories for Savanna-la-Mar (cm)

Water Availability	3 month SPI values	Feb	Mar	Apr	May	Jun
Near normal	0.5	7.0	4.7	5.6	12.1	12.2
	-0.5	3.3	1.1	1.5	5.8	6.6
Abnormally dry	-0.51	3.2	1.1	1.5	5.8	6.5
	-0.79	2.2	0.5	0.6	4.0	5.0
Moderately dry	-0.8	2.2	0.4	0.6	4.0	4.9
	-1.29	0.3	WP	WP	0.9	2.1
Severely dry	-1.3	0.3	WP	WP	0.8	2.1
	-1.59	WP	WP	WP	WP	0.4
Extremely dry	-1.6	WP	WP	WP	WP	0.4
	-1.99	WP	WP	WP	WP	WP
Exceptionally dry	-2	WP	WP	WP	WP	WP

Table 5: Raw available soil water values for the SPI categories for Beckford Kraal (cm)

Water Availability	3 month SPI Value	Feb	Mar	Apr	May	Jun	Sep
Near normal	0.5 -0.5	12.9 7.7	11.8 6.1	11.7 6.0	17.3 9.7	14.9 8.4	16.5 9.0
Abnormally dry	-0.51 -0.79	7.6 6.2	6.1 4.5	6.0 4.4	9.6 7.5	8.4 6.6	8.9 6.8
Moderately dry	-0.8 -1.29	6.1 3.6	4.4 1.6	4.3 1.6	7.4 3.7	6.5 3.3	6.7 3.1
Severely dry	-1.3 -1.59	3.5 2.0	1.6 WP	1.5 WP	3.6 1.4	3.3 1.4	3.0 0.8
Extremely dry	-1.6 -1.99	2.0 WP	WP WP	WP WP	1.4 WP	1.3 WP	0.7 WP
Exceptionally dry	-2	WP	WP	WP	WP	WP	WP

Table 6: Raw available soil water values for the SPI categories for Serge Island (cm)

Water Availability	1 month SPI Value	Feb	Mar	Aug
Near normal	0.5 -0.5	3.8 1.2	2.5 0.3	8.8 4.5
Abnormally dry	-0.51 -0.79	1.1 0.6	0.3 0.0	4.4 3.2
Moderately dry	-0.8 -1.29	0.6 WP	WP WP	3.1 0.8
Severely dry	-1.3 -1.59	WP WP	WP WP	0.8 WP
Extremely dry	-1.6 -1.99	WP WP	WP WP	WP WP
Exceptionally dry	-2	WP	WP	WP

4.0 Discussion

4.1 NDVI and available soil water

The NDVI only had reasonable correlations for months which occur 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 for which good regressions were seen between the NDVI and soil water, 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 water.

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

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

Soil types in this study might have affected the performance of the NDVI correlations to soil water. 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 contents), than in the arenosols (soils with the highest sand contents). Note that the highest R^2 regression coefficient was 0.93, and was achieved for January in Serge Island. It is distinctly possible that the soil type might have been responsible for this. Serge Island has a sandy loam, and by far has the smallest available water capacity of all the soils. It should come as no surprise then, that the best relationship between NDVI and available soil water is seen in Serge Island.

Effect of aridity on relationship between NDVI and available soil water

Within the Jamaican context, due to the high annual rainfall that each of the sites receive, it is no surprise that only 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, from low to high precipitation zones. 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 water in semi-arid Botswana, and this study determined that the NDVI was correlated to the surface soil moisture of the concurrent month of the growing season. Wang et al., (2007) state that in semi-arid environments, NDVI changes closely with soil moisture as soil moisture is the major controlling factor for vegetation. In fact, 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).

<u>Effect of vegetation type on relationship between NDVI and available soil water</u>

Narasimhan et al. (2005) also mentioned that NDVI did not correlate well to soil water 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 shallow root systems that can only extract water from the root zone, 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 helps to explain the generally poor correlations between NDVI and available soil water for the sites.

4.2 SPI and available soil water

One of the main reasons behind attempting to correlate both the SPI and the NDVI to soil water was to give planners concrete information with which to work. In order for drought monitoring networks to be developed within the island, it is important that planners be able to actually apply the information gained from the use of a particular index in a meaningful way. As shown in Table 3, the SPI only had good correlations to available soil water in particular months. A possible reason is that in dry months, the changes in precipitation would be better reflected in soil water. Of course 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 so would still respond to changes in precipitation. Therefore, during May, the increase in rainfall is accompanied by increasing soil moisture, resulting in good correlations.

Tables 4 to 6 show the values of raw available soil water for different values of the SPI. Theoretically, based on the assumptions of the model (Equations 1 and 2), wilting point 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 water values approach wilting point, without actually reaching it. However, the regression curves could not capture this boundary, and as a result the regression equations give ‘negative’ available soil water values for the lowest values of the SPI. Whenever ‘negative’ soil water values were achieved from the regression curves, the numbers were forcibly bounded by assuming an available water capacity of zero, represented as wilting point (WP) in the tables.

Note that for both Savanna-la-mar and Beckford Kraal, the wilting point 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. Interestingly, for Savanna-la-mar, it occurs the latest during the month of June (the lower boundary of the extremely dry category with corresponding SPI value of -1.99), suggesting that soil water during this month exceeds that of May. For Beckford Kraal, wilting point occurs at the same point (the lower boundary of the extremely dry category) in May, however, there is very little difference between the soil water 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 is August, with March again being the driest month. Wilting point occurs at the upper end of the moderately dry category in March, and at the lower end of the severely dry category in August. Note that wilting point occurs at a higher category 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 water is discussed in the following section.

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

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 water in any particular month would have a much smaller dependence on soil water 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 would show a slower response to rainfall, due to the fact that they have much larger water capacities. The soil water conditions in a particular month, would be far more dependent on soil water 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 in which the authors investigated the potential of the SPI and for representing short-term precipitation and soil moisture variation. The authors also suggest that changes in soil types could play a significant role in the relationship between SPI and soil water. In fact, they suggest that SPI time series which have been averaged over longer time periods would have better correlations with soil water in deeper soil layers.

Effect of SPI averaging time period on relationship between SPI and available soil water

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 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. Of course, 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.

5.0 Conclusions

The applicability of both the NDVI and SPI for representing soil water 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 water better in dry years as opposed to wet years, due to a high soil water 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 water 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 water, 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 water, 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 water determined for particular soils. As mentioned previously, the soils within the parish have high spatial variability. Despite this high spatial variability however, it is the hope of the authors that this information (at least until this process has been expanded to account for other soil types) increases understanding of what the SPI values actually mean in a physical context. As a whole, the Caribbean needs to move from a response-driven approach to prevention and mitigation. Therefore, there is significant potential in many ways to apply the use of drought indicators for water resources management within the island.

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