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THE DEVELOPMENT OF TOOLS FOR MANAGING, MONITORING AND ASSESSING WATER STRESSED CONDITIONS IN JAMAICA

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ABSTRACT Agricultural production is an important contributor to the Jamaican economy. However, drought is a serious issue in Jamaica, with the potential to cause millions of dollars in crop losses. In fact, there were crop losses amounting to 6 million USD in the 2000/2001 drought. Therefore, 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 first objective of this paper is therefore to describe the suitability of both the Normalized Difference Vegetative Index (NDVI) as well as the Standardized Precipitation Index (SPI) 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 1 or 3 month SPI was found to be more representative of soil water conditions. The NDVI however, does not provide a suitable representation of soil water for any of the areas studied. The second objective is to disseminate monthly rainfall values of 80% and 90% probability of occurrence for the three locations, in order to facilitate irrigation planning and management by farmers and water managers. To this end, net irrigation demands for vegetables and sugarcane are provided.

Keywords: Standardized Precipitation Index, Normalized Difference Vegetative Index, Net Irrigation Requirements, Water scarcity planning.

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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 Jamaica, 2002).

Rainfall is the most variable climatic parameter in Jamaica. 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 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 Jamaica, 2002). December to March is typically the period with the least rainfall.

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

Agriculture is heavily dependent on rainfall, and in Jamaica, approximately 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. In fact, some estimates indicate that as much as 95% of all domestic agricultural production is rain-fed (Boken 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). It is imperative however, that farmers be provided with the tools to effectively implement their irrigation management plans. Such tools include monthly effective precipitation values.

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 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 and Mehdi, 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.

METHODOLOGY

Study Area Description 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 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.

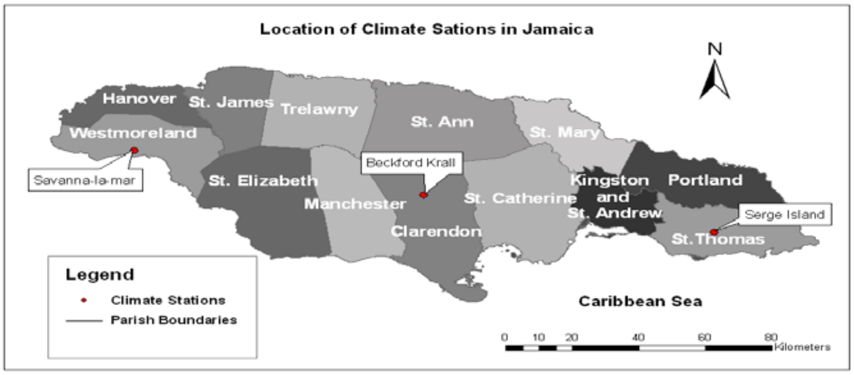

Figure 1: Location of Climate Stations in Jamaica

Savanna-la-mar is located in the parish of Westmoreland, which has 3 distinct growing seasons. These growing seasons range from September to December, January to April, and May to August. Crops such as Irish potatoes, carrots, tomatoes, sweet peppers, cauliflower and cabbage are grown during the months of September to April in two rotations of three to four months each, while perennial crops such as pineapples, papayas, plantains and bananas are harvested during the summer months (May to August) (Mitchell, 2010, *personal communication*). Loam soil was the dominant soil type at the Savanna-la-mar site.

Beckford Kraal is located in the parish of Clarendon, and 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 (a green leafy vegetable), carrots, cauliflower, lettuce, pak-choy, cabbage and pumpkins etc. Clay soil was the dominant soil type at Beckford Kraal. Lastly, at the Serge Island site, 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 was 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.

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, and as such was deemed appropriate for use in the Jamaican context. 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:

$$L_s = \min\left[S'_s, \left(ET_p - P\right)\right] \tag{1}$$

$$L_u = \left(ET_p - P - L_s\right)\frac{S'_u}{w_{ac}}, \text{ provided that } L_u \le S'_u \tag{2}$$

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, 2000).

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. 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 abnormally low rainfalls during the September to November during the period of 1970 to 1980. It was assumed that the soil at June 1 was at field capacity.

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 Difference Vegetative Index (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 vegetative 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 that were most relevant to a particular month were then averaged in order to obtain monthly NDVI values. These monthly values were then correlated to concurrent monthly soil water, as well as monthly soil water lagged by both one and 2 months, in order to see if good relationships existed between the two parameters.

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 (2009). The SPI was developed for the 3, 6, 9 and 12 month periods for the three study sites. The monthly rainfall data was obtained directly from the Jamaica Meteorological Service 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.

Determination of Net Irrigation Requirements The net irrigation requirement was derived from the relationship modified from Savya and Frenken (2002):

$$IR_n = ET_c - (Pe + Ge + SWa) + LR_{mm} \quad (3)$$

(Savya and Frenken, 2002)

Where:
IR_n = Net Irrigation Requirement (mm)
ET_c = Monthly Crop Evapotranspiration (mm)
Pe = Monthly Effective Dependable 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 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 1) to determine Etc values for each crop. A pan coefficient of 0.85 was used, and was chosen based on the type of pan, fetch, and meteorological characteristics of the relevant areas (Allen et al., 1998).

Table 1: 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**	0.7	1.05	1.05	1.05	0.7	1.05	1.05	1.05	0.7	1.05	1.05	1.05
	Sugarcane	0.75	0.75	0.4	0.4	1.25	1.25	1.25	1.25	1.25	1.25	1.25	0.75

Effective Rainfall (Pe) In order to determine Pe, a frequency analysis was done for each month, using the 38 year monthly rainfall data for each station. The most suitable probability distribution function (PDF) was fitted to the data, using the Matlab® software. 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 Generalized Extreme Value PDF was found to be the best fit for the vast majority of months for each station. However, there were a few months for which the Gamma PDF provided the best fit.

In order to determine the net irrigation requirements for each station, the 80% and 90% dependable rainfalls were found for each month, for each station. These values were chosen based on recommendations for irrigation planning by Savya and Frenken (2002). The 90% dependable rainfall was used for the months of December to March, as this season experiences the least amount of rainfall. For the months of May to November however, the 80% dependable rainfall values were used. In order to determine monthly effective rainfall, the following empirical equation was used (Bos et al., 2009):

$$Pe = f \times (1.253P^{0.824} - 2.935) \times 10^{0.001ET_c} \quad (4)$$

(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 applied per turn (-)
P = the dependable precipitation per month (mm/month)
ET_c = the total crop evapotranspiration per month (mm/month)

f is calculated as such:

$$f = 0.133 + 0.201 \ln D_a \quad if\ D_a < 75\frac{mm}{turn} \tag{5}$$

and

$$f = 0.946 + 7.3 \times 10^{-4} \times D_a \quad if\ D_a \geq \frac{75mm}{turn} \tag{6}$$

(Bos et al., 2009)

Pe was calculated for three depths of irrigation water applied per turn: 40 mm, 75 mm and 110 mm. Only the results for an irrigation depth of 75 mm are shown in this paper however.

Groundwater Contribution from Water Table Groundwater table data has been collected by the Water Resources Authority 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 specific areas for which this study was taken place. As a result, it was deemed as appropriate to ignore groundwater contribution to crop water requirements. However, despite this assumption, it is very possible that in some areas, especially in area surrounding Savanna-la-mar, that groundwater does contribute to the soil moisture content.

Monthly Plant Available Water The monthly plant available soil water was calculated as shown using equations 1 and 2.

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 LR is location specific, and will need to be determined for each specific location and situation. As such, the LR was ignored for these calculations.

RESULTS

Correlation of Drought Indicators to Soil Water The NDVI showed no correlation to soil water, for any of the three stations. In fact, the NDVI experienced minimal changes throughout the 9 year time period for which it was extrapolated. As such, for the areas for which the NDVI was developed, it can be reasonably stated that is not a relevant indicator of water scarce conditions, at least for the three study locations.

On the other hand, the three month SPI showed reasonable R^2 correlations (≥ 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 correlations for Serge Island, and reasonable correlations were only seen for the months of May, June and August (Table 2).

Table 2: 3 month SPI correlations to monthly soil water for Savanna-la-mar, Beckford Kraal and 1 month SPI correlations for Serge Island

Month	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
Savanna-la-Mar	0.6	0.8	0.8	0.7	0.8	0.8	0.6	0.5	0.4	0.4	0.4	0.5
Beckford Kraal	0.5	0.7	0.8	0.7	0.9	0.7	0.6	0.6	0.7	0.5	0.3	0.3
Serge Island	0.4	0.6	0.6	0.4	0.7	0.7	0.6	0.7	0.5	0.5	0.6	0.6

Dependable rainfall and net irrigation requirements The 80% and 90% monthly dependable rainfalls were determined for each station, and these, as well as net irrigation demands, are shown in Table 3 and 4 respectively.

Table 3: Dependable Rainfall for Savanna -la-mar, Beckford Kraal and Serge Island

		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

Table 4: Net Irrigation Demands for Vegetables and Sugar Cane for Savanna-la-mar, Beckford Kraal and Serge Island

Cimate Station	**Crop**	**Net Irrigation Requirement at end of month (mm)**											
		JAN	**FEB**	**MAR**	**APR**	**MAY**	**JUN**	**JUL**	**AUG**	**SEP**	**OCT**	**NOV**	**DEC**
Savanna-la-Mar	Vegetables	1	70	102	78	0	0	0	0	0	0	0	25
	Sugarcane	7	33	10	0	0	1	2	0	0	0	0	0
Beckford Kraal	Vegetables	0	0	39	45	0	11	45	101	0	0	0	0
	Sugarcane	0	0	0	0	0	32	64	115	0	0	0	0
Serge Island	Vegetables	37	90	129	164	11	57	78	38	0	0	0	53
	Sugarcane	43	54	35	51	90	86	110	66	20	11	19	16

DISCUSSION The NDVI has been found to be well-correlated to monthly mean soil moisture values in previous studies (Farrar et al., 1994). The NDVI was found to represent soil water better in dry years as opposed to wet years however, due to a high soil water availability during wet years, allowing for very little change in NDVI values (Narasimhan et al., 2005). Narasimhan et al. (2005) also found that the NDVI provides a good representation of soil moisture, and as such can be used as a good agricultural drought indicator. However, as stated in the previous section of this paper, the NDVI showed minimal change throughout time, and had no correlation to soil water. Narasimhan et al. (2005) did mention however, that NDVI did not correlate well to soil water for brush species in rangeland and trees in forest land, however it responded well to changes in soil water for agricultural and pasture lands. In Jamaica, typical family farms are small scale (between 10 to 20 ha), and some can be under 2 ha (WRCL, 2009). In addition, these farms are typically 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 brush-land or woodland. As such, the ability of the NDVI to represent soil water is limited for the island, unless areas with expansive agricultural schemes are chosen. There are however, areas where expansive sugar cane and citrus plantations exist, and it is recommended that the NDVI be compared to soil water in these areas in order to assess whether or not better correlations could be obtained. It should also be noted that the soil type might also be affect the performance of the NDVI correlations to soil water. As clay soils tend to retain water for much longer than sandy soils, changes in precipitation might not be reflected in the vegetation as readily as it would in a sandy soil. This should also be taken into consideration when it comes to future attempts at relating NDVI values to 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. Admittedly, the SPI only had good correlations 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 in all three locations. 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 saturated, or even at field capacity, and would therefore still respond to changes in precipitation. Another interesting result is that the three month SPI has significantly better correlations than the one month SPI for both Savanna-la-mar and Beckford Krall, but not for Serge Island. Keeping in mind the fact that the dominant soil type at the Savanna-la-mar site was a loam soil, while the dominant soil at the Beckford Krall site was clay, it is likely that the soil type played a large part in this result. The dominant soil type at the Serge Island site was a sandy loam, which responds very easily to precipitation conditions, due to its limited water holding capacity. Therefore, 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 has no historicity, showing no dependence on 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. As such, 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 SPI may be more useful in monitoring agricultural drought.

Another 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 other soils) at least increases understanding of what the SPI values actually mean in a Jamaican context. The authors would like to point out that the categories of the SPI defined elsewhere (such as in the U.S.), cannot and should not be universally applied to all locations, and attempts should be made to determine what the SPI actually represents in the local context.

According to the historical trends, the period of December to April actually receives the least amount of rainfall. Incidentally, this is also the period during which cane is reaped, as it allows for the cane to sweeten. For Savanna-la-mar, the only months to require irrigation (for vegetables) are the months of December to April, although the net irrigation requirement for January is very small. For Beckford Kraal however, the months that need irrigation (for vegetables) are March and April, as well as June to August. Serge Island needs irrigation in every month (for vegetables), except in September, October and November. Overall, these results highlight the importance of not depending on rainfall data alone, but taking a look at all components of the water balance.

CONCLUSION Net regional irrigation requirements were calculated for sugarcane and vegetable crops for the three study areas, for both wet and dry growing seasons, and for 80% and 90% precipitation exceedance probabilities. Each study site is unique in its irrigation requirements, which highlights the climatic variability across the island. However, all three sites are similar in their need for irrigation during the months of March to April, signifying that this is a universally dry period across the island. These estimations will go a long way in eliminating the uncertainty in irrigation management and development.

Finally, the applicability of both the NDVI and SPI for representing soil water conditions in Jamaica was also evaluated. The NDVI was not found suitable for the areas evaluated. 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 3 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. It is hoped therefore that the results from this research will help Jamaica develop an effective agricultural drought management framework.

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