Scientific Research Publishing

Journal of Geoscience and Environment Protection, 2023, 11, 69-89
https://www.scirp.org/journal/gep
ISSN Online: 2327-4344
ISSN Print: 2327-4336

Designing a Drought Monitoring System for Caribbean SIDS

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How to cite this paper: Alexander, K., & Thongs, G. (2023). Designing a Drought Monitoring System for Caribbean SIDS. *Journal of Geoscience and Environment Protection, 11,* 69-89.
https://doi.org/10.4236/gep.2023.112006

Received: November 30, 2022
Accepted: February 24, 2023
Published: February 27, 2023

Abstract

There are limited drought studies for the Caribbean. This is concerning since drought is not only one of the most devastating disasters in the region, but it is also one of the least understood disasters. Very few papers analyze new ways to identify and monitor this disaster. Another major arguable gap in research is the Caribbean's sole focus on the meteorological drought and disregard of the agricultural drought. This is an important omission because of the significant negative impacts drought has on the Caribbean occurs in the agricultural and forestry sectors. Not considering this in drought monitoring systems in the Caribbean means that a major part of the phenomena is overlooked. Therefore, this study has focused on bridging this gap. It has sought to establish a system to strengthen drought's early warning. To accomplish this, three predetermined conditions of drought, precipitation, land surface temperature and vegetation conditions were used to derive the Standard Precipitation Index (SPI), the Temperature Condition Index (TCI) and the Vegetation Condition Index (VCI), in order to analyze drought conditions. The drought vulnerability map found that the SPI, TCI and VCI all correlated with past drought events. The study also produced an agricultural drought map. This study, therefore, aims to build resilience by providing accurate information on the duration, intensity and spatial variability of droughts in Caribbean Small Island Developing States (SIDS).

Keywords

Drought, Climate Change, Caribbean, SIDS, GIS, SPI

1. Introduction

According to McGregor (2015), drought is a complex natural disaster that affects large numbers of persons either directly or indirectly. It is a slow creeping disaster that gives little warning till its onset (Wilhite et al., 2014). Its presence is only known in most cases when its impact has already reached a crucial state. Consequently, drought is the least prepared for disaster. Early warning signals are difficult and, in many instances, non-existent in some countries (Chopra, 2006).

Belal et al. (2014) defines drought as the product of a place's exposure to the natural hazard and its vulnerability to extended periods of insufficient rainfall for the plant growth in order for it to complete its life cycle. It is the degree to which a population or an activity is vulnerable to the effect of drought. The more exposed a population or activity is to drought, the higher the risk. Therefore, a drought risk assessment seeks to improve the understanding of the drought hazard and the factors that influence the vulnerability with the aim to mitigate its impact.

The risk assessment process is usually divided into 3 major stages (Belal et al., 2014). The first stage is to accurately identify the hazard. The spatial extents, frequency and severity of such phenomena are crucial in the identification process. The second stage in drought risk assessment is the identification and quantification of drought vulnerability. This involves identifying the persons who are most vulnerable to droughts. Drought vulnerability is dynamic, and examines the increasing population, the advancement of technology, the absence of natural resource influences, the desertification processes, and the use of water trends. Identifying drought vulnerability requires a multi-factor analysis (Belal et al., 2014).

The third and final stage in drought risk assessment literature is the computation of drought risk patterns. GIS, and by extension, remote sensing has been used in many studies to conduct drought risk assessments. It is described a unique style of not only visualizing the drought hazard in order to understand the complexity, but also to provide calculations to estimate the probable loss or damage caused by the drought hazard. Consequently, GIS technology, through the use of remote sensing indices, have the ability to monitor and model the damage caused by this slow onset disaster.

The use of remote sensing indices to monitor drought has been widely implemented in India, Sri Lanka, China, Europe and Africa (Alahacoon, Edirisinghe, & Ranagalage, 2021; Kloos et al., 2021, Moisa, Bobo, & Gemed, 2022; Mupepi & Matsa, 2022; Talukdar et al., 2022; Zhao et al., 2022). The most widely used of these were the TCI, SPI and VCI indices. Unfortunately, one major drawback of the existing literature is that few, if any, research case studies examine the Caribbean small island developing state context. Since 1992, the Caribbean SIDS was recognized as a special case both for their environment and development. Factors like small population size, as well as fragile land and marine ecosystems make Caribbean SIDS particularly vulnerable to climate change and disasters, like drought.

2. The Problem

Drought is of serious concern to the Caribbean region due to its climatic nature and its social, economic and environmental vulnerability. With the change in climatic conditions, it has become more frequent (Niggli et al., 2022). The region stands ready to suffer from extreme variation in rainfall events. This has been supported by Christensen et al. (2007) which projected that the annual decrease of precipitation can amount to five to fifteen percent. This will cause an increase in the annual mean temperature value of the region. Therefore, the region will experience warmer days and nights and as a result, more frequent drought events (FAO, 2016). Water management such as construction of more dams, water harvesting, the use suitable method of irrigation can decrease the effects of drought.

In addition to the increasing likelihood that a trend of drought will occur in the Caribbean, the region is progressively becoming more vulnerable to the disasters. Over the last decade, the Caribbean suffered US $3.3 billion in losses due to climatic disasters (EM-DAT, 2008). Additionally, drought has been projected to cost the Caribbean approximately US $3.8 million annually in relief actions (ILO, 2021).

Drought increases the demand of water while decreasing the supply, leaving a sizeable gap and causing social unrest in some communities (Farrell, Trotman, & Cox, 2011; Kong et al., 2016). According to Caribbean farmers, the 2020 dry seasons were the worst dry season experienced within the last generation. Water levels at the national dams were the lowest they have been in 30 years. Also, the period of the drought coincided with the on-set of the COVID-19 pandemic which doubled the impact of the pandemic, particularly for the most vulnerable of society. The long-term drought that occurred in 2019 and 2020 resulted in the absence of a consistent and reliable access to potable water to some countries in the Caribbean. This is especially true for Caribbean residents who already struggle with poor daily sanitation and no access to potable water, which has become essential during the COVID-19 pandemic. Consequently, it has become exceedingly difficult for the region to mitigate and respond to these two major shocks in such quick succession.

3. The Problem

Drought studies have been limited in the Caribbean region. This lack of research is problematic since drought has become a part of the Caribbean climate and is one of the most devastating natural disasters in the region. The few drought studies available mostly focus on either the impact of drought on the Caribbean or the social and economic vulnerability (Herrera et al., 2020, Seidenfaden, Jensen, & Sonnenborg, 2021, Curtis & Gamble, 2008). Very few speak about limiting the impact of drought by finding new ways to identify and monitor this slow onset disaster, and implementing mitigative actions to ensure fewer devastating events.

In 2010, the Caribbean Institute for Meteorology and Hydrology (CIMH), was mandated to develop a comprehensive approach to monitor and predict drought in the region (FAO, 2016). The CIMH set up a Caribbean Drought and Precipitation Monitoring Network where they monitor drought at both a national and regional scale. The major indices used to monitor and predict drought were the Standard Precipitation Index and the Decile Index. They concentrate mainly on the meteorological type of drought in the Caribbean by investigating the rates of rainfall. The CIMH provides short term and seasonal precipitation forecasts, projecting future drought occurrences (Caribbean Institute for Meteorology and Hydrology, 2015).

This highlights another major arguable gap of research in the Caribbean. Currently, there is a heightened focus on meteorological drought and neglect of the agricultural type drought. The most significant negative impacts drought has on the Caribbean occurs in the agricultural and forestry sectors. Not considering this type of drought in drought monitoring systems in the Caribbean means that a key aspect of the phenomena is overlooked. No study was found that focused primarily on agricultural drought in the Caribbean or sufficiently includes it with the meteorological and hydrological drought monitoring systems.

Therefore, this study will focus on bridging this gap in the research regarding agricultural type drought techniques with drought monitoring in the Caribbean region. It is hoped that it can be used to establish a system that will strengthen drought early warning in the Caribbean (FAO, 2016).

Trinidad and Tobago and Drought

Trinidad is one of the twin islands in the Republic of Trinidad and Tobago and occupies 4826 km^2 of land area. Trinidad and Tobago have a population of 1.4 million people (CSO, 2016). The islands are located within close proximity to the equator and have a tropical climate. As such, two opposing seasons are experienced, known as the wet and dry seasons. The dry season occurs during the first five months of the year, from January to May, and the wet season occurs from June to December. The dry season, according to the MET Office of Trinidad and Tobago, is characterised by moderate to strong low-level winds, warm days and cool nights, and conventional rainfall in the form of showers due to daytime. The wet season is characterised by low level winds, hot days and nights and increased rainfall. The annual average maximum temperature in Trinidad is 31.3 degrees Celsius, while its annual minimum temperature is 22.7 degrees Celsius. The island experiences a mean daily temperature of 26.5 degrees Celsius. September is known as the warmest month in the wet season while March is known as the warmest month in the dry season. June is primarily the most active month for rainfall in Trinidad.

Like many other Caribbean countries, Trinidad and Tobago is susceptible to a multi-hazard environment where a drought was experienced during the COVID-19 pandemic. That interaction of two disasters raised the awareness and the critical need for not only analysing each of these individual disasters but more importantly, a deeper consideration of the long-term interplay of these two disasters occurring at the same time. From the onset, the concurrent presence of the two hazards has not only put great strain on the short-term health and social emergencies, but also great strains on the economy.

Meanwhile, the likelihood of a severe drought occurring in Trinidad and Tobago has been on the rise. The country has experienced frequent abnormal dry periods, better known as dry spells, over the past decade. For example, a dry spell was recorded during the first four months of 2017. A dry spell is categorised as the climatic stage just before a drought. If these conditions continue, the chances for the dry spells graduating and becoming drought are very high.

Geographic Information Systems (GIS) and Remote Sensing (RS) techniques can capture, analyse and monitor the weather behavioural trends to properly inform drought activity. GIS/RS are best suited to identify vulnerable areas and help policy makers mitigate the risk the country may be exposed to, and aid in making sustainable decisions.

As a result, the objectives of this research were to design a GIS/RS based drought monitoring system; and to develop a drought hazard map for Trinidad. It should also be noted that the proposed drought monitoring system that was developed for Trinidad can be applied and implemented in all Caribbean countries to assess and analyse the drought issues that are already being faced.

4. Identification and Acquisition of Data

The first stage in developing the GIS and RS drought monitoring system was the identification and acquisition of required data. To accurately analyse the contributing factors of drought, the primary data needed for this study were identified as precipitation, land surface temperature, and normalised differencing vegetation index (NDVI).

4.1. Precipitation Data

Precipitation data accounts for the meteorological influence in the drought analysis. It measures the accumulated rainfall per month in millimetres and is the only data to be used in deriving the Standard Precipitation Index (SPI) (Zargar, Sadiq et al., 2011). Precipitation data was acquired from two sources for this study, one from directly measured values and the other from remotely sensed derived estimates. The measured rainfall values were used to validate the estimated rainfall data, which was used in the study.

The direct measured precipitation data was sourced from the Trinidad and Tobago Meteorological Service. They recorded daily rainfall measurements in millimetres at their two stations, in Piarco, Trinidad. The results were tabulated and subsequently used to verify the liability and accuracy of the remote sensed estimated rainfall data.

4.2. Land Surface Temperature Data

Land surface temperature was the second primary data used in this study. It was used because it is a reliable positive indicator in assessing evapotranspiration, vegetation water stress, soil moisture and thermal inertia (Karnieli et al., 2010).

Land surface temperature is a predetermined condition that is expected to show variation when a drought is occurring. The best practices of accurately measuring land surface temperature with high spatial reference are done using remote sensing satellite missions.

4.3. NDVI Data

NDVI is used to provide remote sensed information on the health of vegetation cover. This is done using the reflectance values of visible and near infrared bands of the electromagnetic spectrum to assess the presence of vegetation and its health conditions. The advancement of remote sensing technology has made the NDVI a popular indicator of drought (Karnieli et al., 2010).

Literature has shown that the NDVI can be used as a response variable to identify and quantify drought disturbance, where low values will indicate vegetation stress. Vegetation stress can be either caused by a lack of rainfall, increased temperature or an invasion of some pest or disease. In normal situations, vegetation stress is caused by the lack of rainfall and increased temperature and, as such, NDVI values have become an effective indicator of drought (Karnieli et al., 2010).

In addition to the primary data, other supporting data was required to assess the drought hazards. These data were sourced from online GIS data resources such as DIVA GIS for this study. It included: land use of Trinidad; major river networks in Trinidad and finally reservoirs/water bodies.

5. Methodology

Figure 1 presents an illustration of the system used to monitor the occurrences of drought. It identifies how the acquired data was processed and combined to produce an effective drought monitoring system. It shows the stages in processing the data and the steps undertaken to overlay the indicators to produce the required drought hazards maps.

5.1. The Standard Precipitation Index (SPI)

The validated precipitation dataset was used to compute the SPI at a different time scale. This study used the recommended scale period of three and six months since the drought period investigated was of a short scale. To calculate the SPI, the first was to normalise the rainfall data using the transformation function $f(P)$:

$$f\left(P\right) = \sqrt[3]{P}$$

where P is the precipitation sequence.

Secondly, the respective rainfall datasets were sum based on the SPI scale of use. The three-month SPI for January, and the three-months leading up to January inclusive of January were added together for every year. The accumulated rainfall for November, December and January were derived for all the years. The following equation was used to calculate rainfall data for the three-month SPI:

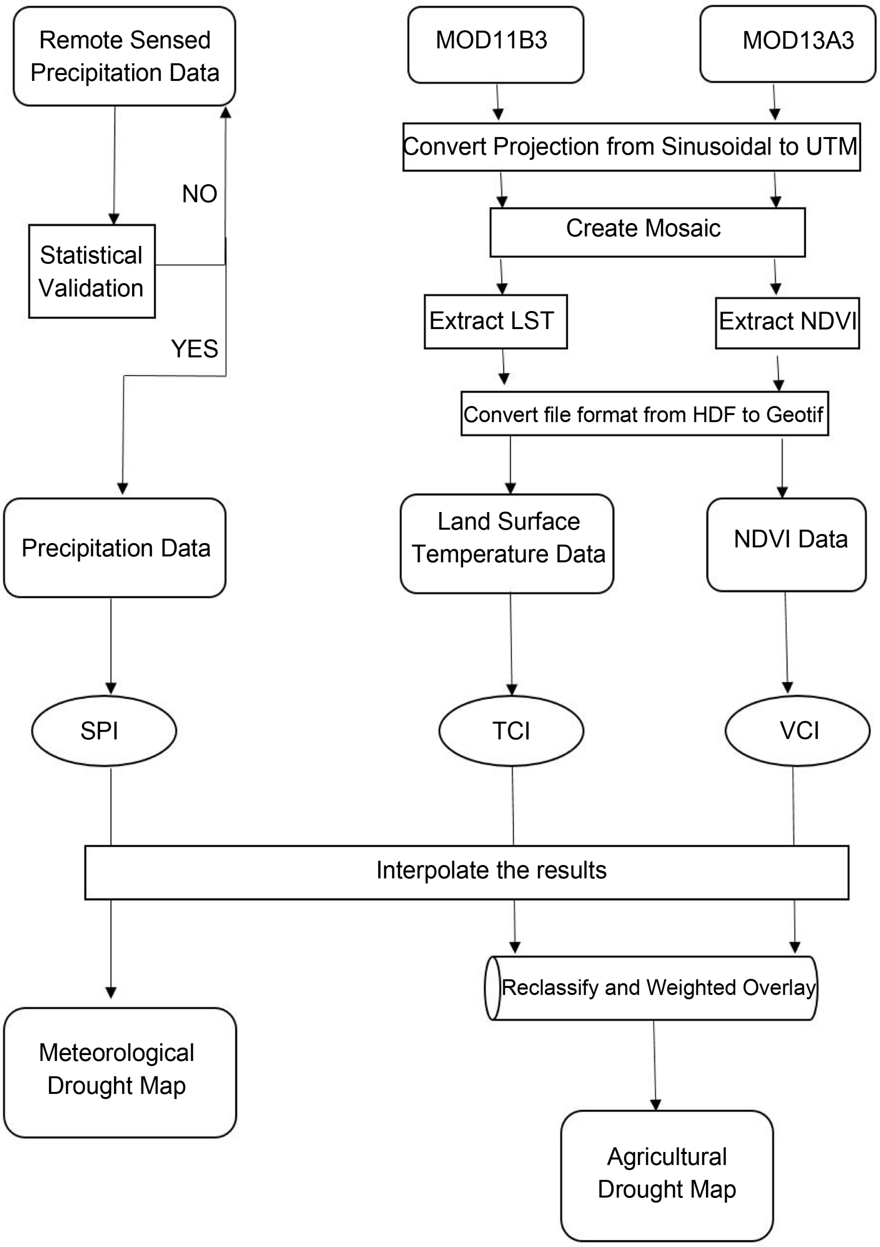


Figure 1. Methodology of drought monitoring system.

$$R_n + R_{n-1} + R_{n-2} = R_{An} \quad \text{(three-month SPI)}$$

where R_n is the accumulated rainfall for specified month, $R_{n\text{-}1}$ is the accumulated rainfall for the 1st month preceding the month n, $R_{n\text{-}2}$ is the month accumulated rainfall for 2nd month preceding the month n and R_{An} is the accumulation of rainfall for three months inclusive of the month n.

Thirdly, the total mean and standard deviation of the normalised precipitation were computed using the cell statistic tool in ArcMap

$$\text{The Standard Deviation} = \sigma = \sqrt{\frac{\sum\left(R_{An} - \overline{x}\right)^2}{N}}$$

The Total Mean $\bar{x} = \frac{\sum R_{(An)i}}{N}$ where $i = 1983$ to 2016 and N is 33.

Finally, the SPI was calculated using the following formula:

$$\mathrm{SPI}_i = \frac{f(P)_i - f(P)_m}{f(P)_\sigma}$$

where $f(P)_i$ is the normalised precipitation for the period (i), $f(P)_m$ is the mean normalised precipitation over the years, and $f(P)_\sigma$ is the standard deviation of the normalised precipitation values for the same period.

5.2. The Temperature Condition Index (TCI)

The TCI index was chosen to identify drought events based on the thermal condition of the land surface. The processed MOD11B3 dataset was used to compute the TCI. Firstly, a dataset representing the maximum and minimum temperatures for the respective months was derived using the ArcGIS Cell Statistic tool. Then the TCI was computed using the equation below in the raster calculator in ArcMap.

$$\mathrm{TCI}_i = T_{\max} - \frac{T_i}{T_{\max} - T_{\min}} \times 100$$

where $T_{\max}$ is the maximum temperature for the period and $T_{\min}$ is the minimum temperature for the period, and T_i the temperature at a given time. The TCI values are represented as a percentage. The presence of drought is suggested from values ranging from 50% to 0% where 0% suggests the most extreme drought conditions.

5.3. The Vegetation Condition Index (VCI)

The processed monthly NDVI values were used to compute the Vegetation Condition Index. First, the maximum and minimum NDVI datasets per period were derived, using the cell statistic tool in Arc Map. After, the VCI values were calculated using the equation below in the raster calculator in ArcMap:

$$\mathrm{VCI}_i = \frac{\mathrm{NDVI}_\mathrm{I} - \mathrm{NDVI}_{\min}}{\mathrm{NDVI}_{\max} - \mathrm{NDVI}_{\min}} \times 100$$

where $\mathrm{NDVI}_{\max}$ and $\mathrm{NDVI}_{\min}$ are the maximum and minimum NDVI values of a given period and NDVI_I is the NDVI of a given time of i. The VCI values were represented as a percentage for easy understanding. Normal healthy conditions are defined by 50% or more, while 50% and less suggest stress vegetation with 0% being very extreme stress conditions. Therefore, as the value decreases from 50% and tends towards 0%, drought conditions increase in severity, with 0% being the most severe.

5.4. The Drought Hazard Map Development

The products from the SPI, TCI and VCI were used to produce drought hazard maps. The SPI, TCI and VCI represent the three types of drought hazards that this study investigated. From these two drought hazard maps were created: the meteorological drought hazards map and the agricultural drought hazards map. The SPI result was used to produce the meteorological drought hazard map, while the TCI and VCI were combined to produce the agricultural drought hazard.

The products of the SPI, TCI and VCI were interpolated using the local polynomial interpolator method to produce a smooth, continuous surface map. Once the data was interpolated, it was then ranked and reclassified. Table 1 below shows the ranking and reclassification scheme used.

The TCI and VCI were then combined, using the weighted overlay tool and assigned them equal weights. This product formed the Agricultural Drought Hazard Map.

5.5. Validation of Rainfall Data

To validate the liability and accuracy of the Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS) rainfall dataset, the following was employed. Firstly, the GPS coordinates of the Trinidad and Tobago meteorological station were obtained. The position was identified on the CHIRPS rainfall dataset and its values for every month for the period 1985 to 2016 were extracted and tabulated. The extracted CHIRPS rainfall value was compared with the corresponding measured data from the meteorological station. The values were tested for correlation using the Pearson formula:

Table 1. Classification scheme of the SPI, TCI and VCI.

Indices	Classification Scheme	Rank	Classification of Drought
SPI	>0	1	No Drought
	$-1 < x \le 0$	2	Abnormal Dry
	$-1.5 < x \le -1$	3	Moderate
	$-2 < x \le -1.5$	4	Severe
	≤ -2	5	Extreme
VCI	$50 < x \le 100$	1	No Drought
	$35 < x \le 50$	2	Abnormal Dry
	$25 < x \le 35$	3	Moderate
	$10 < x \le 25$	4	Severe
	≤ 10	5	Extreme
TCI	$50 < x \le 100$	1	No Drought
	$35 < x \le 50$	2	Abnormal Dry
	$25 < x \le 35$	3	Moderate
	$10 < x \le 25$	4	Severe
	≤ 10	5	Extreme

$$r = \frac{n\left(\sum xy\right) - \left(\sum x\right)\left(\sum y\right)}{\sqrt{\left[n\sum x^2 - \left(\sum x\right)^2\right]\left[n\sum y^2 - \left(\sum y\right)^2\right]}}$$

Pearson's law of correlation identifies the linear relation between two variables.

The results range between −1 and +1 where +1 means perfect positive correlation and −1 means perfect negative correlation and zero means scatter data that is no correlation. The linear relationship between the measured precipitation value versus the extracted value from the CHIRPS rainfall dataset is expected to be positive for the CHIRPS rainfall dataset to be approved as reliable and accurate. The measured data should normally increase and decrease as the CHIRPS rainfall dataset increase and decrease in its value.

In addition to testing the correlation of the monthly values, the maximum, minimum, mean and standard deviation were also analysed for every month. Once the results were close to +1, the dataset was then allowed to be used in the SPI calculation. If the data did not meet the required standard, it could not be used in the calculation of SPI values, since it would produce inaccurate results. New datasets representing precipitation would have to be acquired.

A statistical analysis was also done on the CHIRPS rainfall and the data from the meteorological station's monthly mean values. The Pearson Coefficient was found to be 0.98, indicating an almost perfect positive correlation. That meant that the CHIRPS rainfall dataset was a valid source to provide good historical information on rainfall in Trinidad. Hence, it was a good dataset to be used in SPI computations to derive drought occurrences. Figure 2 below shows the spread of the mean values between the CHIRPS rainfall values and the measured precipitation values.

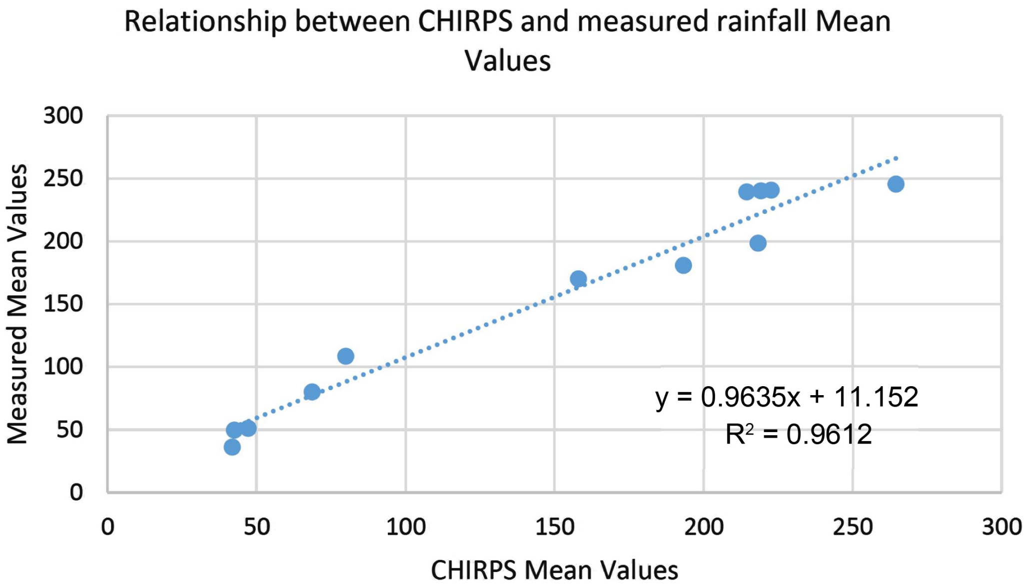


Figure 2. Scatter-plot of CHIRPS rainfall monthly mean values and measured mean values.

6. The SPI Product of Trinidad

The SPI maps at both three-month and six-month scales for the whole of 2009 and 2010 were generated. The years 2009 and 2010 were chosen because they represented normal and drought conditions for the island. The Trinidad and Tobago Office of Disaster Preparedness and Management (ODPM) noted that Trinidad experienced drought in the last quarter of 2009 and the first quarter of 2010.

The evolution of the drought for the period 2009 to 2010 was shown using the SPI maps. The three-month and six-month SPI scales were chosen to best capture the drought event that was recorded to have lasted for 6 months on the island. The 1 month and 12 month SPIs were also tested. However, the results proved incapable of capturing the drought conditions sufficiently because of their short and large scales, respectively.

The values of the SPI ranged from +3 to −3, with +3 representing extreme wet conditions, −3 representing extreme drought conditions, and 0 representing normal conditions. These values were represented in various colours on the maps. Positive 3 values were shown as a dark blue colour, negative 3 values were shown as a dark red colour, and 0 values were shown as a light green colour on the map. As the conditions moved away for the normal to extreme drought conditions, the colour is shown to change from light green to yellow to light orange to dark orange to red and then to dark red. Likewise, as the conditions moved away from normal to extremely wet conditions, the colour is shown to change from light green to dark green to sky blue to blue and then to dark blue.

Comparing the three-month and six-month SPIs for 2009 and 2010, it was found that they both positively identified the drought occurrences, however, at slightly different temporal values. The three-month SPI found that the drought started in November of 2009 (**Figure 3**) and was continuous till the end of March in 2010 (**Figure 4**). The six-month SPI, on the contrary, found that the drought event started in October 2009 and end in April 2010, with an ease in the drought conditions in February 2010. The three-month SPI also showed that the island experienced moderate drought conditions in June and July of 2009.

Both scales found that the intensity of the drought for the period was classified as severe. The most intense drought conditions were experienced in the upper half of the island with significant concentration on the eastern side (**Figure 5**, **Figure 6**). The southwestern peak of the island also commonly experienced the most intense drought conditions. The south-central area of the island experienced the least severe conditions in the midst of the drought disaster.

6.1. The TCI Product for Trinidad

The TCI results found that there was a short period of moderate drought spread across the island in June and July of 2009 (**Figure 7** June 2009 and July 2009), which was outside of the documented drought period by the ODPM for the years 2009 and 2010. These results were consistent with the three-month SPI

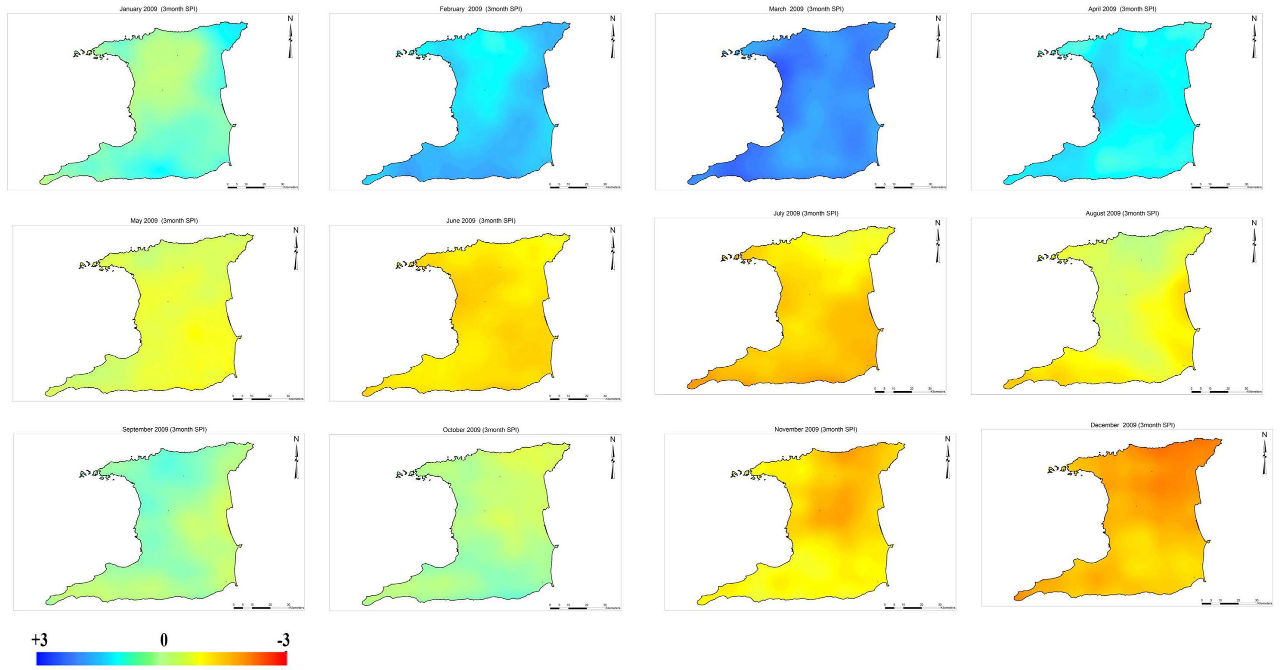


Figure 3. Three-month SPIs of Trinidad for the period January-December 2009.

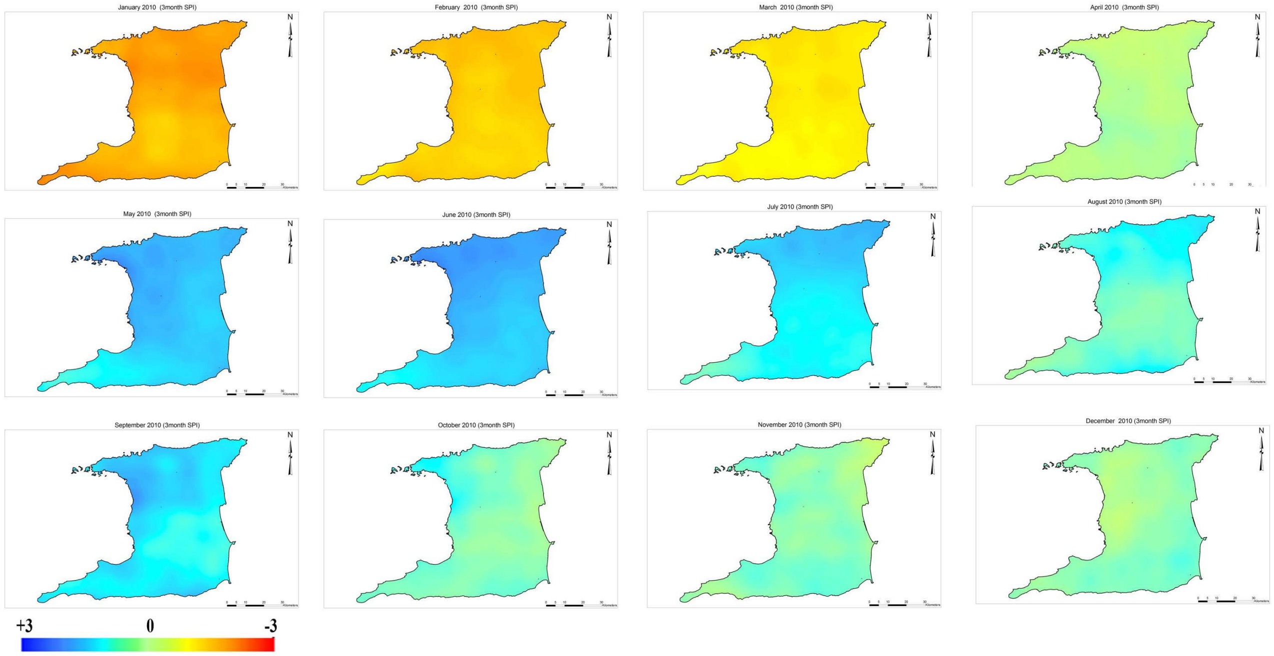


Figure 4. Three-month SPIs of Trinidad for 2010.

results explained in the section above. After that short period of drought, the TCI continued to show certain patches of drought conditions across the island in the preceding months. Nonetheless, the drought like conditions was not significant until November 2009. In November 2009, more than three quarters of the island experienced some form of drought conditions with extreme conditions concentrated in the south-eastern, central-western, central-eastern and

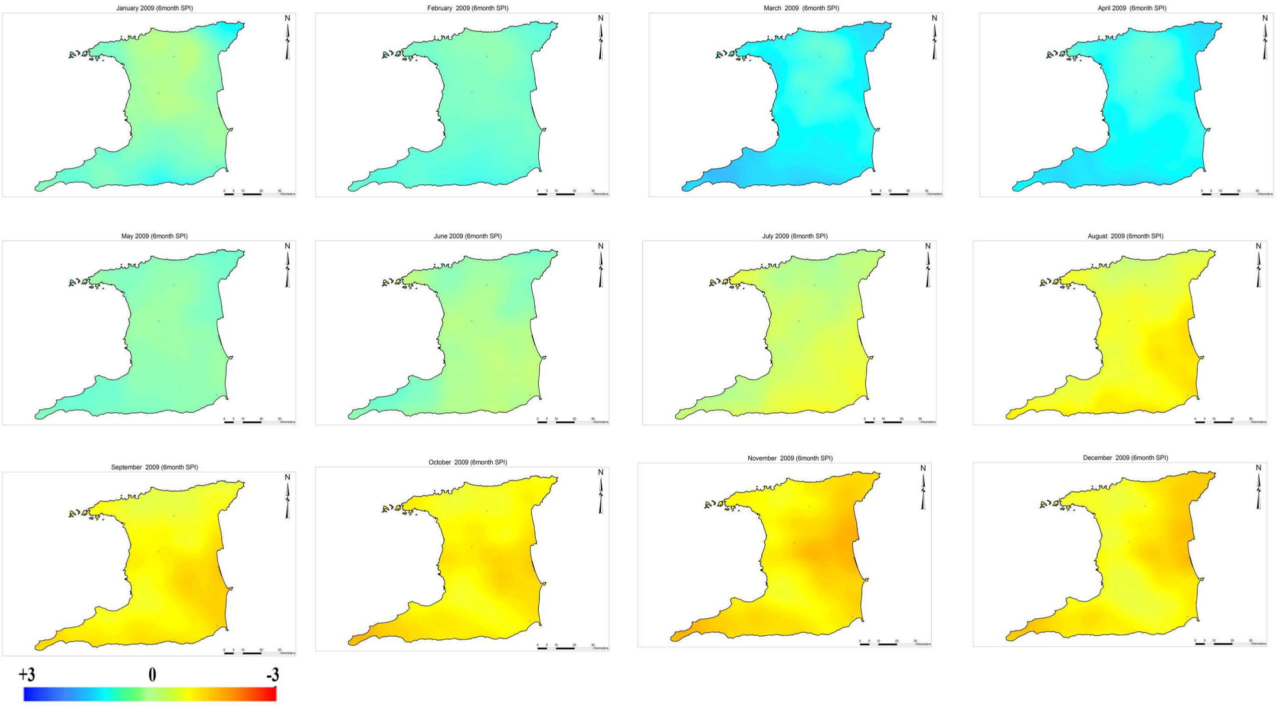


Figure 5. Six-month SPIs of Trinidad for the period 2009.

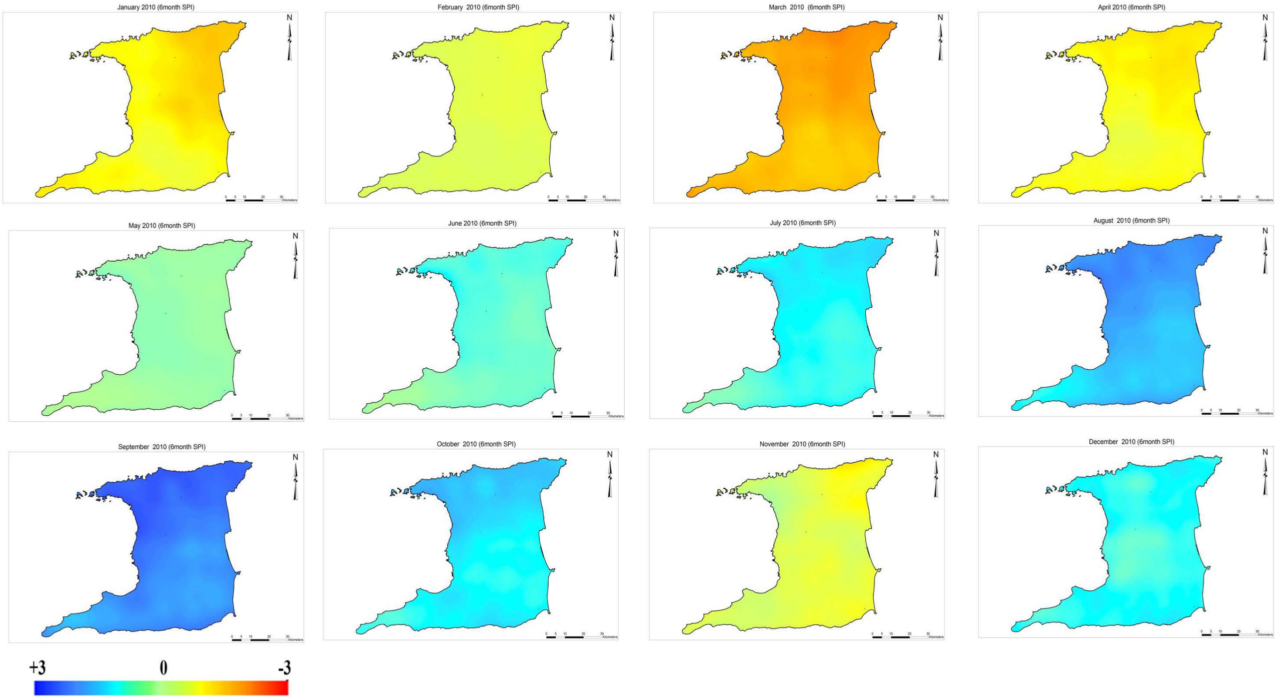


Figure 6. Six-month SPIs of Trinidad for the period 2010.

north-central parts of the island (**Figure 8** November 2009).

In January 2010, more than 80% of the country was coloured red on the TCI map with a few displays of orange in the south part of the island. This indicated that the majority of the island experienced extreme drought conditions.

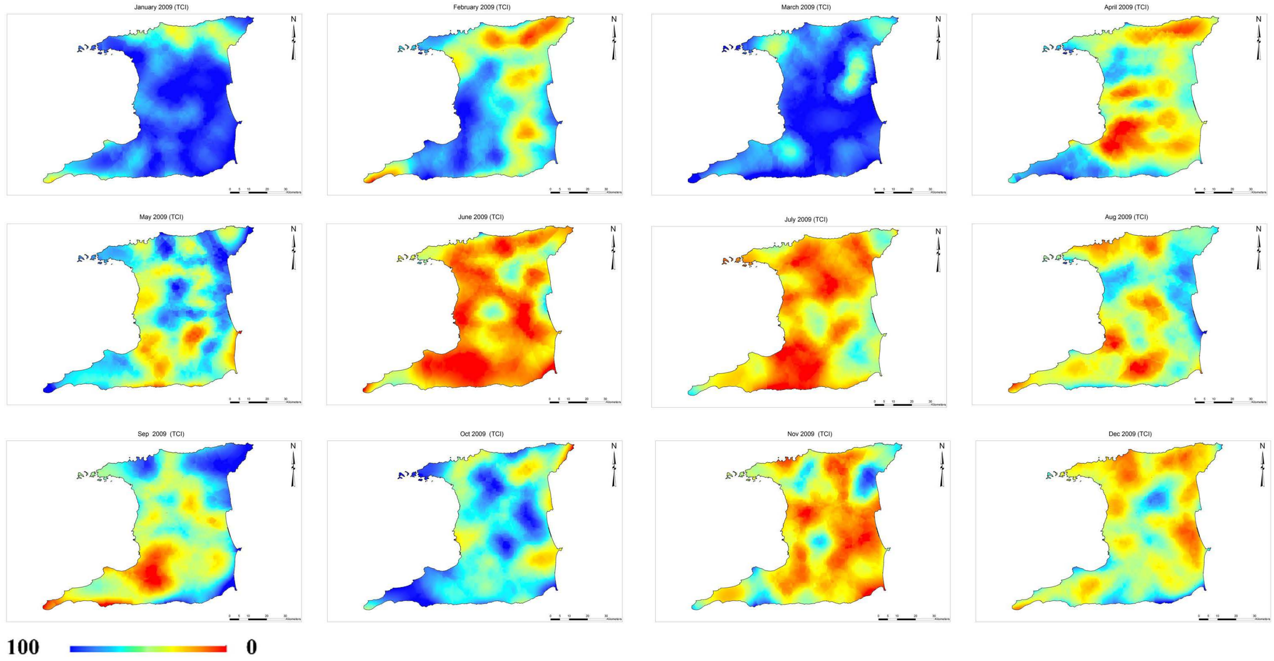


Figure 7. TCI results of Trinidad for the period 2009.

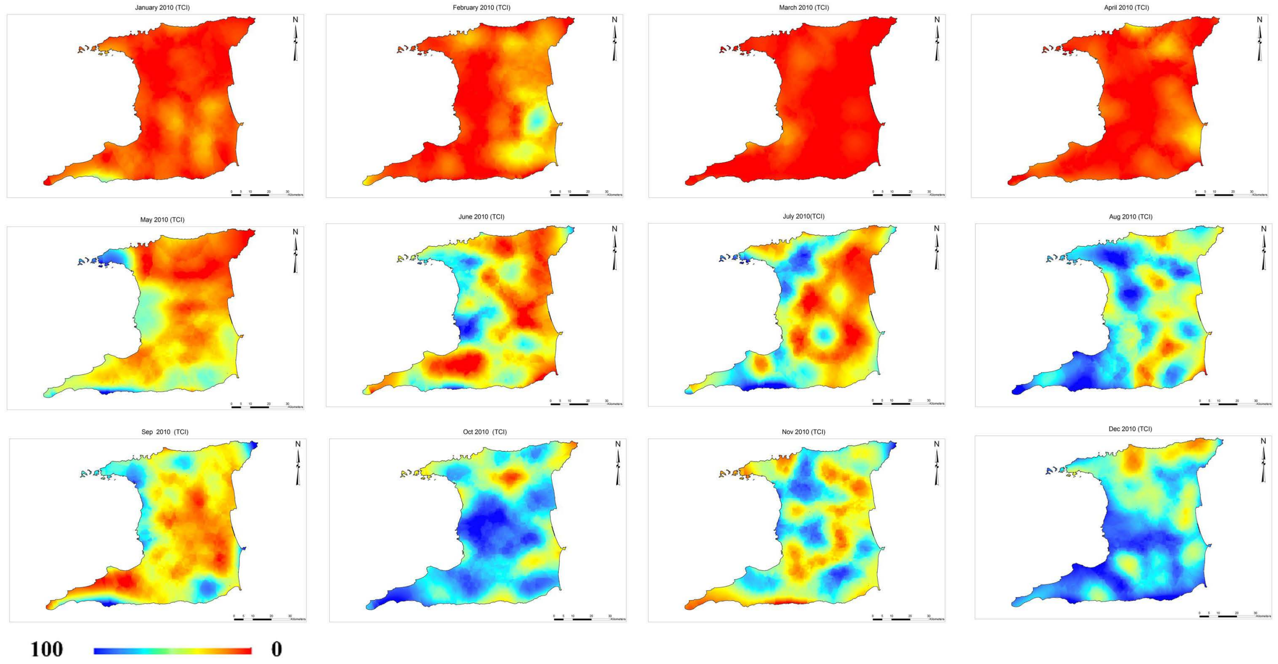


Figure 8. TCI results of Trinidad for the period 2010.

6.2. The VCI Product for Trinidad

The Vegetation Condition Index was produced using MODIS monthly NDVI satellite images (MOD13A3). The VCI values were computed for every month from 2001 to 2016. Its values, like the TCI, range from 100 to 0. The higher values represented positive vegetation growth and healthy vegetation conditions, while 0 represented negative growth and unhealthy vegetation conditions. Dark green represented the high VCI value, dark red represented the low VCI value, and yellow represented the median VCI value. The median value of 50 described normal conditions and, as the value decreased to 0, the colour changed from yellow to orange to red, increasing the intensity of extreme drought conditions.

The maps shown in **Figure 9** and **Figure 10**, illustrate the evolution of the VCI values for 2009 and 2010.

During the rainy season, the soils are moister, which provide positive conditions to support healthy vegetation. Vegetation grows rapidly in such condition and its VCI value is usually high. More green colouring can be seen for such period that experienced heavy rainy conditions. Conversely, during the dry season, more red colouring is evident since vegetation health deteriorate due to a lack of soil moisture and the rising land surface temperature. Therefore, when there was an increased red colouring for any given period, it was understood that it indicated the presence of drought conditions.

Drought was identified for the period February to May 2010 using the VCI values. The dark red colouring could be seen more distinctly during these periods than any other during the observation period. It covered roughly 80% of the island in March and April of 2010, with an average VCI value of 24 for the island. Based on the classification scale used in this study, such a value suggested that the entire island had experienced severe drought conditions for the period.

Consequently, the results of this study have confirmed the theory, whereby the drought SPI identified extreme drought conditions before the VCI. However, such differences in the time lag could not have been identified with the VCI and

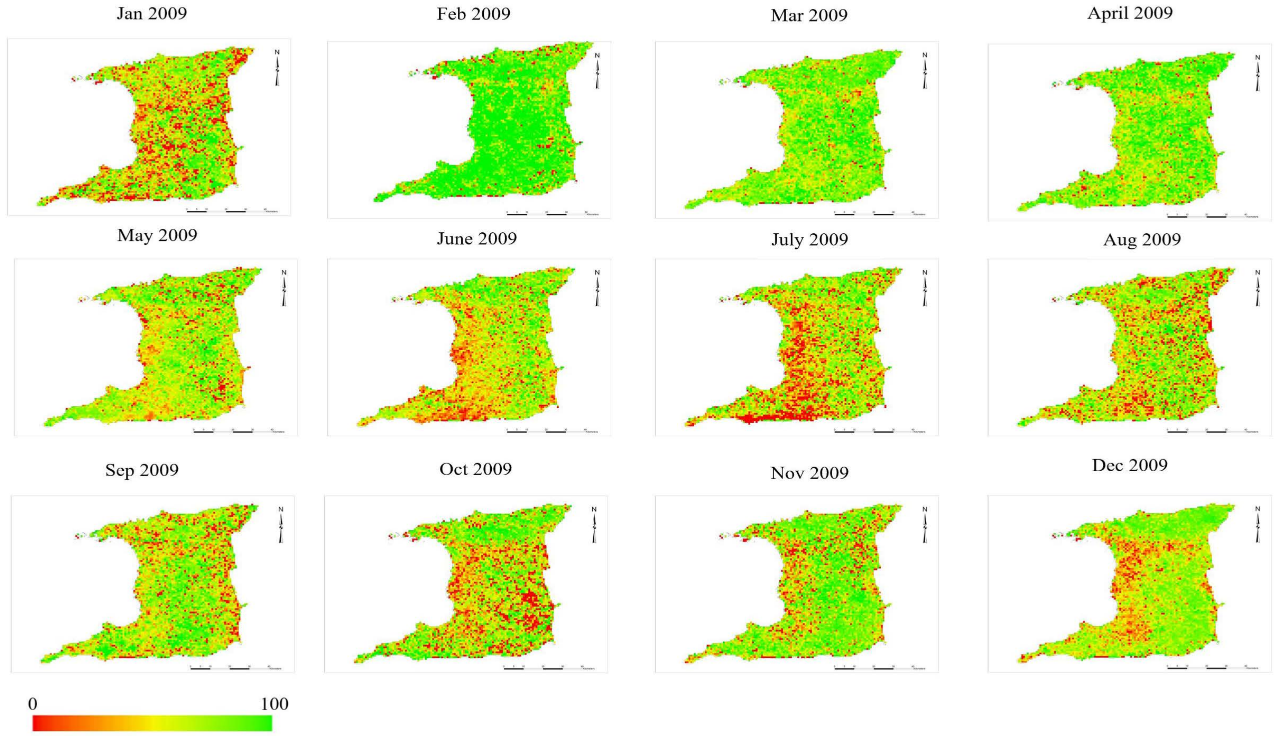
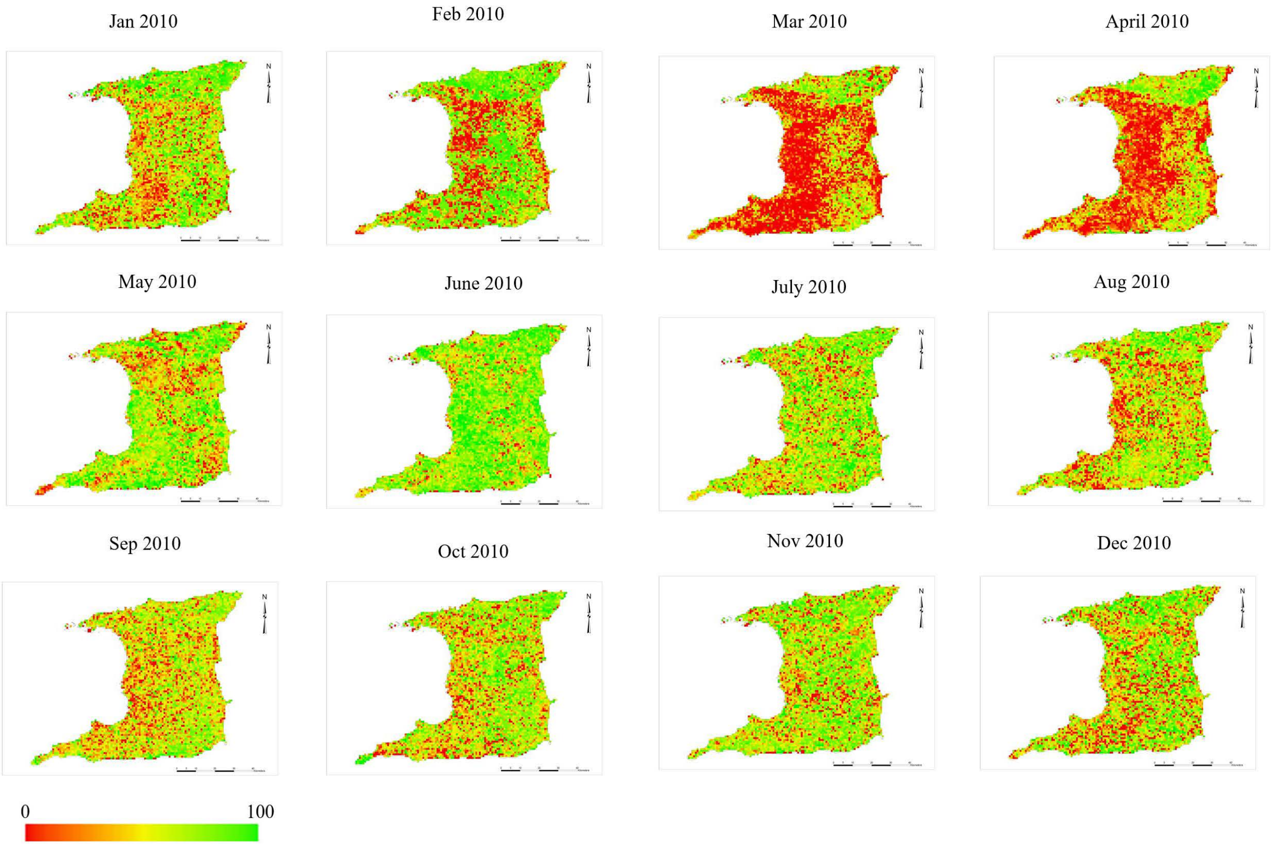


Figure 9. VCI results of Trinidad for the period 2009.



Jan 2010 · Feb 2010 · Mar 2010 · April 2010 · May 2010 · June 2010 · July 2010 · Aug 2010 · Sep 2010 · Oct 2010 · Nov 2010 · Dec 2010

Figure 10. VCI results of Trinidad for the period 2010.

the TCI in this study because the observation period used was larger than the responding period. Therefore, both the VCI and the TCI correlated well in identifying the 2009-2010 drought period for the island of Trinidad.

6.3. The Drought Hazard Maps

The hazards are represented in two drought hazard maps. The first being the meteorological drought hazard map and the other being the agricultural drought hazard map. The meteorological drought hazard map was created from the product of the SPI while the agricultural drought hazard map was created from a combination of the TCI and the VCI product. The hazard maps were re-classified into five classes: no drought, dry spell period; moderate drought; severe drought and extreme drought.

Specific years were selected to capture severe drought, normal and wet period. The years 1998 (**Figure 11**) and 2010 (**Figure 12**) represented the severe drought conditions, while the year 2007 represented the normal condition.

The red represents extreme drought conditions, orange represents severe conditions, yellow represents moderate conditions, green represents abnormally dry conditions, and blue represents the absence of drought hazards.

In January 1998, extreme meteorological drought hazards were found in the south western and south central part of the island. Severe conditions were most

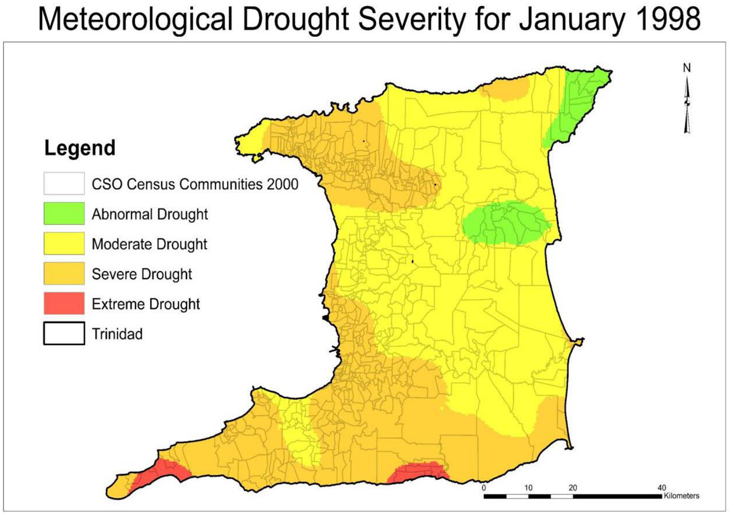


Figure 11. Meteorological drought hazard for January 1998 and 2010.

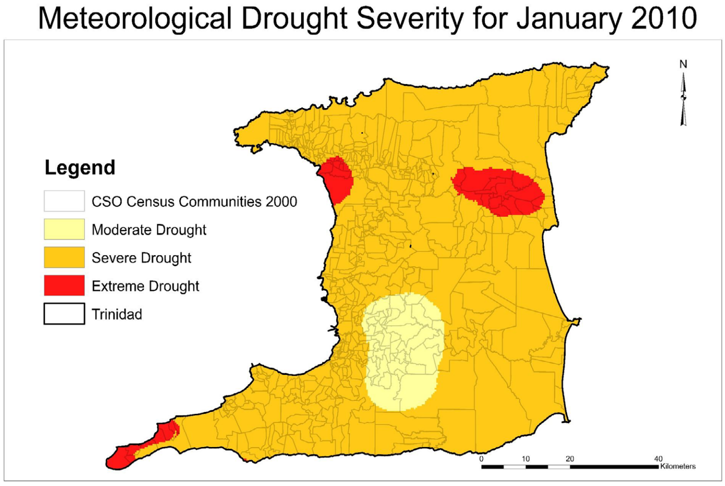


Figure 12. Meteorological drought hazard for January 2010.

concentrated in the southern and north-western part of the island. The remaining portion, which was the largest portion of the island, apart from the north-eastern and central-eastern, had experienced moderate conditions. In January 2010, 87% of the island had experienced severe drought condition while 6% extreme drought condition and 8% moderate drought condition (**Figure 12**).

During the drought period of April 2010, a significantly large portion of the island, 42%, was exposed to an extreme agricultural hazard. Severe drought condition was spread throughout 28% of the island while moderate drought was classified to be on 29.3% of the island. A minimal 0.7% of the island was not classified to have experience drought (**Figure 13**).

7. Drought in the Caribbean

This study has established that there is a research gap in the Caribbean where there is a heightened focus on meteorological drought and neglect of the

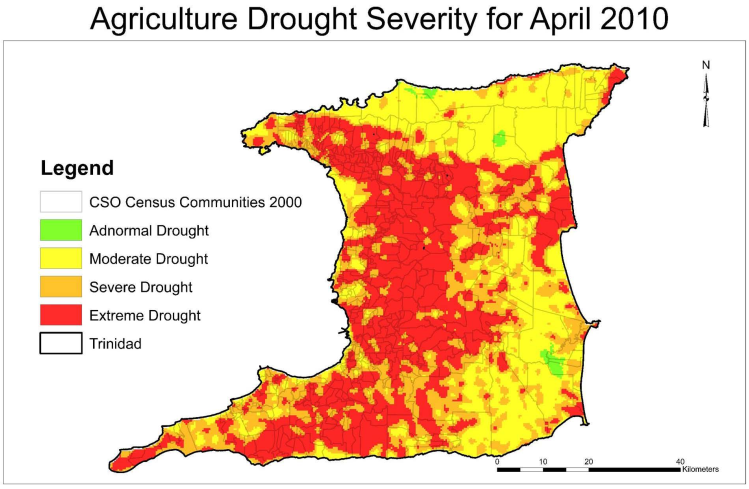


Figure 13. Agricultural drought hazard map for April 2009 and 2010.

agricultural drought analysis. Not considering this type of drought in drought monitoring systems in the Caribbean means that a key aspect of the phenomena is overlooked. No study was found that focused primarily on agricultural drought in the Caribbean or sufficiently includes it with the meteorological and hydrological drought monitoring systems.

This is a gap that needs to be addressed due to the significant negative impacts that drought has on the Caribbean which occurs in the agricultural and forestry sectors. Thus, this study sought to focus on bridging this gap in the research regarding agricultural type drought techniques with drought monitoring in the Caribbean region. Thereby, creating a monitoring system that will strengthen drought early warning in the Caribbean.

This highlights another major arguable gap in the Caribbean as currently, there is a heightened focus on meteorological drought and neglect of the agricultural type of drought. The most significant negative impacts drought has on the Caribbean occurs in the agricultural and forestry sectors. Not considering this type of drought in drought monitoring systems in the Caribbean means that a key aspect of the phenomena is overlooked.

In order to achieve this, the products of the SPI, TCI and VCI were interpolated using the local polynomial interpolator method to produce a smooth, continuous surface map. Each of these indices were back casted to ensure that they accurately represented and correlated with known drought events recorded by the Trinidad's disaster management office.

The three-month and six-month SPI scales were chosen to best capture the drought event that was recorded to have lasted for 6 months on the island. The one month and twelve-month SPIs were also tested. However, the results proved capable of capturing drought occurrences than any other method currently used in Caribbean SIDS. Hence, the recommendation of using this new system.

This GIS/RS drought monitoring system will produce maps, reports and tables to better explain the conditions of drought events to its end users. Maps will easily identify locations of the drought hazard via the use of colours and graphics. The system also allows for the drought hazards to be overlaid with common thematic layers, to give a visual understanding of the drought in relation to the possible threat to society. For example, the overlay on various thematic layers like community layers, road networks, major river networks, and census data, will explain to end users who, what and how many may be directly at risk from the drought hazard.

Once the results are verified, the next advantage of this proposed system will be its ability to disseminate information to a wide audience or end users. Information on drought conditions can be easily shared via a web GIS to persons in urban and rural locations, particularly farmers. Through the use of technology, rural and urban smart phone users will be able to use their devices to identify which drought zone they belong to. Therefore, this system can relate common information on the most misunderstood natural disaster to a wide audience, ranging from policy makers to organisation managers to technocrats to the average man on the street.

Although there were many advantages to this study, a few limitations were encountered. Firstly, it should be noted that soil moisture data was not used because it was not easily accessible for the study area. Secondly, there was an overall lack of measured rainfall data in the public domain. Lastly, the process to acquire measured rainfall data from the Water Resource Agency was complicated and did not meet the timeframe of the study.

8. Conclusion

The study investigated the use of GIS and Remote Sensing techniques to properly monitor drought in Trinidad. It was successful, whereby the Remote Sensing techniques positively identified the last severe drought in Trinidad. This proves that such a method can be used for the effective monitoring of drought activities in Caribbean SIDS. It can identify the slow onset of a drought at an early stage, determine the drought intensity, calculate the duration of the drought, and determine the spatial impact of the drought.

The GIS and Remote Sensing Drought Monitoring System used three indicators of drought and three indices to assess the drought conditions. Precipitation, land surface temperature and vegetation condition were the indicators used, while the SPI, the TCI and the VCI were two indices employed together to identify the meteorological and agricultural drought hazards.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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