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RESEARCH ARTICLE

A RESILIENT DROUGHT RISK MANAGEMENT APPROACH IN THE SEMIARID NORTHEAST BRAZIL

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ABSTRACT

Droughts in Northeast Brazil, which tend to intensify due to climate change, have repeatedly brought famine, mass migration and social conflicts in this region. Its prediction, monitoring and management, however, remain a central research theme. In water resources management in semiarid regions such as the Northeast of Brazil, it is fundamental to have tools to aid decision making. This paper presents three components of the so-called SIGES (Drought Management System), the items related to drought prediction and monitoring, as well as many reservoir operation methodologies for water scarcity situations. Statistical models, artificial neural networks and machine learning techniques were used for drought prediction. In order to perform precipitation monitoring, several indexes were adapted and incorporated into a droughts basic characteristic monitoring system (duration, severity and intensity), so that different mitigating actions could be implemented in accordance with the values reached by these parameters. We utilized the following meteorological indexes for this purpose: Rainfall Anomaly Index (RAI); Bhalme and Mooley Drought Index (BMDI); Lamb Rainfall Departure Index (LRDI). Finally, some reservoir operation for water scarcity situations methodologies are presented and discussed. The described components were applied to the Northeast of Brazil, especially Piauí, Ceará and Rio Grande do Norte states.

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INTRODUCTION

Marengo (2006), Salati *et al.* (2007), Brito *et al.* (2017) conducted studies on the impacts of global climate change for many areas of Brazil, as Brazilian Amazon, Northeast, Pantanal and the Prata River Basin, showing precipitation and temperature anomalies, and water balance for the XXI century. The semiarid northeastern presenting short but crucially important rainy season in the current climate could, in a warmer climate in the future, become arid. To the northeast, Salati *et al.* (2007) assessing climate variability in the region, showed that the average temperature increased by 0.6°C within the period 1991 to 2004, when referred to the period from 1961 to 1990. For maximum temperature values they indicated a 0.6°C increase and for minimum temperature values a 0.5ºC raise. The precipitation decreased 153 mm, a 11.6% drop. Nobre *et al.* (2004) indicate that the future biomes distribution in South America may be affected by the combined impacts of climate and land use changes, which can take the system to the savannization of parts of the Amazon and the desertification of Northeast Brazil. In relation to the observed values, the ensemble model mean values tend to be large in much of Africa, the Northeastern region of South America (northeastern Brazil), and northwest North America, and small in northern low latitudes of the Americas and southern South America. The arithmetic mean streamflow of 12 IPCC models for the period 2041-2060, when compared to the 1900-70 period A1B scenario for the rivers of northeastern Brazil showed a 15% reduction (Milly *et al.,* 2005). Several studies have indicated the influence of numerous atmospheric phenomena on rainfall in Northeast Brazil (Moura and Shukla, 1981; Hastenrath, 1984; Freitas and Billib, 1996; Uvo *et al.,* 1998; Andreoli and Kayano, 2007; Moscati and Gan, 2007; Rusteberg and Freitas, 2018). Also several climatological studies have indicated the existence of a strong relationship between sea surface temperature distribution (SST - sea surface temperature) along the tropical Atlantic basin temperature and the semiarid northeastern Brazil precipitation, as well as a decadal trend associated with changes in the meridional position of the ITCZ - Intertropical Convergence Zone (Moura and Schukla, 1981; Rao and Hada, 1990; Billib and Freitas, 1996). These phenomena are indicative to be related to climate variability and extreme droughts and floods in the region. Droughts can be characterized as a natural phenomenon sharply differenced from other natural catastrophes. Unlike other natural occurrences as floods, hurricanes and earthquakes, that start and end at sudden, being restricted into a small region, drought phenomena are used to have quite often a slow start, a long duration, and is generally spread out through a wide area (Freitas, 1997). Drought is known as a recurrent phenomenon in semi-arid regions. The lasting effects of a drought in a particular region depend, however, not only on the duration and intensity of drought, but also of socio-economic and cultural rights of the affected population. The occurrence of drought in regions where the water demand is greater than water availability or where there is a large variability of supply water, almost always bring large scale consequences. Large irrigation projects and densely populated urban concentrations are subject to a huge vulnerability with regard to water supply. During drought periods there is also a significant decrease in hydroelectric power generation. Billib and Freitas (1996) presented a methodology for integrated regional drought analysis, which briefly consists of the following topics: (1) definition of different types of drought, (2) forecasting and monitoring: (3) water resources management and optimization, (4) effects evaluation and (5) planning of mitigating actions. Freitas and Billib (1996) demonstrated the feasibility of using prediction models for the dry northeastern Brazil: statistical-probabilistic models and models based on neural networks. Drought periods forecasting and monitoring are particularly useful for Northeast Brazil due to, among many others, the following: (1) the existence of numerous irrigation projects implemented and being implanted along major rivers, (2) supply water of large cities is mostly dependent on direct runoff from rivers or, indirectly, on the volume accumulated in dams, (3) most agricultural crops depend only on the regularity of the rains, (4) the possibility of using groundwater is small as compared to that of surface water and (5) most of the region's energy production is based on hydropower (Freitas, 2005). It is a notorious fact the extreme need for implementation of Decision Support Systems – DSS, like SIGES – Drought Management System, in order to provide the policy makers, ie the decision makers (politicians, state secretaries, coordinators, etc..) of the various government agencies (at federal, state and municipal level) of skilled and practical instrumental, especially those related to water resources management, for the prediction and monitoring of dry and wet periods in semi-arid regions.

Drought prediction

The dry and wet years forecast is of vital importance for essentially agricultural semiarid regions (Billib and Freitas, 1996). The semi-arid region with an area of more than 1 million km², is characterized by a large temporal and spatial precipitation variability, resulting in a process of main watercourses intermittency. It is clear the urgency of implementing models in order to reduce these uncertainties. The model therefore includes the analysis of dynamic weather causes ie the analysis of the global circulation system, especially ENSO (El Niño - Southern Oscillation), as well as surface Atlantic Ocean temperature anomalies (Atlantic Dipole phenomenon). Several methods have been applied during last century in order to predict droughts in northeastern Brazil. Attempts, for example, were performed in order to relate the number of sunspots and total rainfall. Correlations between various variables such as air pressure, temperature, sea surface temperature and other from distant regions and annual precipitation in the Northeast were analyzed at the beginning of the last century.

Figure 1 shows a simplified diagram proposed by Freitas (2005) for drought management. This management system subcomponent of the integrated regional drought analysis consists of statistical methods application (correlation analysis, contingency tables, principal component analysis etc.), artificial neural networks, fuzzy logic etc. for rainfall forecasting. Another possible method would be to forecast sea surface temperature (SST) 6 or even 12 months in advance and then the total rainfall in a region through simulation using a global atmospheric-oceanic circulation model. The latter path however requires greater computational cost.

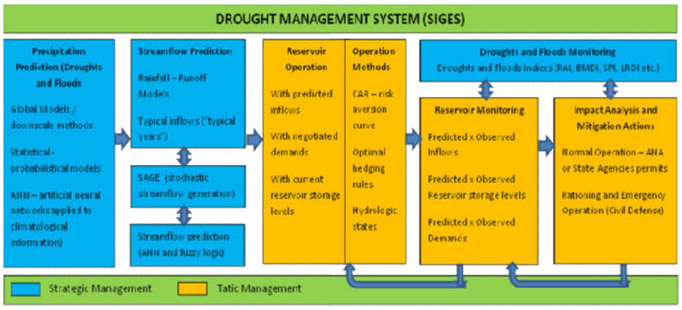

Figure 1. Drought Management System (SIGES)

ENSO (El Niño - Southern Oscillation)

Besides the influence of the Intertropical Convergence Zoneposition', among other things, several authors have reported possible connection between El Niño and Southern Oscillation and the behavior of rainfall in Northeast Brazil. Ropelewski and Halpert (1987) among others have addressed this relationship.

Figure 2 shows the alternations between wet and dry periods and years ENSO - El Niño / Southern Oscillation, for the Cearástate according to Rasmusson and Carpenter (1983). The rainfall rate used was LRDI (Lamb Rainfall Departure Index) that expressed the regional rainfall deviation related to the mean, in terms of standard deviations (Lamb *et al.* 1986).

It is easy to see that, generally drought years occur after El Niño phenomenon occurrence years. This happened in the years 1914, 1918, 1930, 1941, 1951, 1953, 1957, 1965, 1969, 1971, 1982, 1986, 1992 and 1997. The year following an El Niñoyear, however, is not always a dry year, as seen in 1912, 1924 and 1926. There are also dry years that did not follow El Niño years, such as 1936 and 1979. El Niño is related to the Pacificsea surface overheating, nearby Peru and Equator coasts. South Oscillation, by its turn, is related to air pressure difference between Darwin (12º 20'S, 130º 52'E) and Tahiti (17º 33'S, 149º 31'W).

Statistical Models

The identification of meteorological causes and the development of drought forecasting methods in northeastern Brazil were made by analyzing theglobal circulation phenomena, especially the ENSO (El Niño-Southern Oscillation). Correlations between precipitation in Northeastern Brazil and circulation related parameters, such as sea surface temperature (SST) and pressure difference in the Pacific (Tahiti-Darwin), allow future rainfall estimates. Regression analysis and the use of conditional probability tables were employed using rainfall data from the Northeast of Brazil, in addition to Pacific Ocean sea surface temperature and air pressure data. In order to establish the model, the years were classified as, humid, normal and, dry, based on its probability of rainfall exceedance. Initial statistical analysis was based on thirty rainfall stations well spatially distributed in the Cearástate, in order to observe the dependence severity between El Niño incidence and droughts occurrence in Ceará.

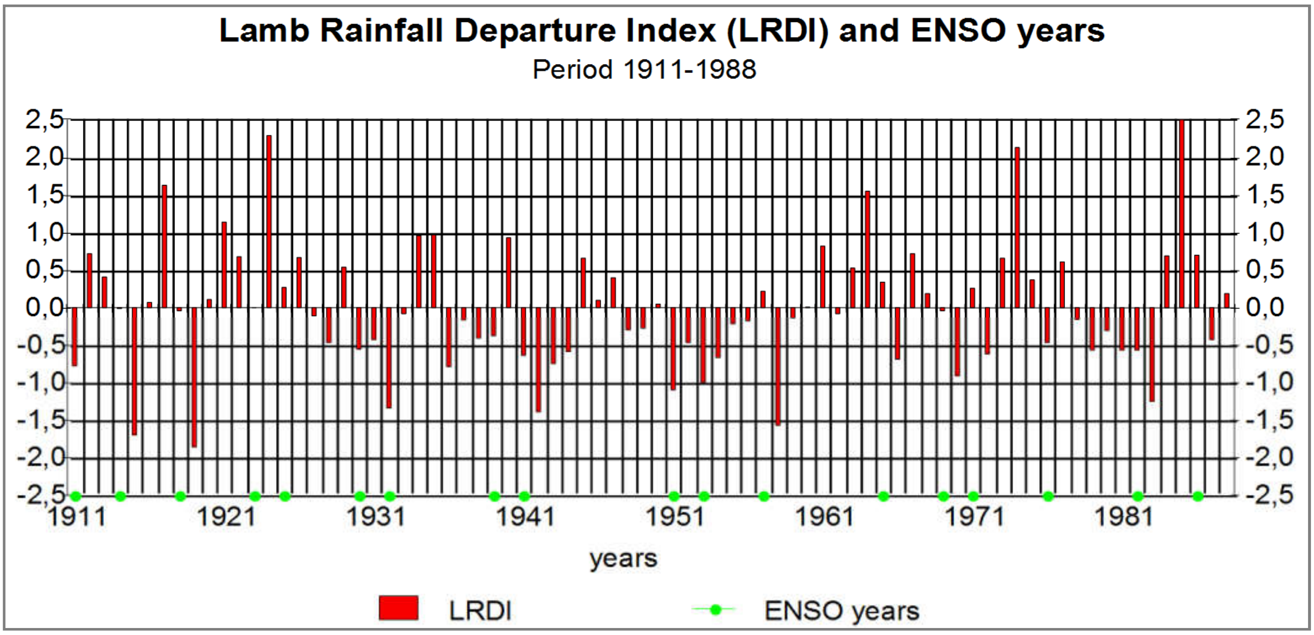

Figure 2. Dry and wet periods alternancy and ENSO years, from 1911 to 1988, in Ceará State (NE Brazil), according to Rasmusson and Carpenter (1983)

Additionally, we have established conditional probability tables for different stations. The 33% and 67% quantiles of the rainfall series were used to classify years in dry, normal or wet. ENSO Indexes were also classified into warm, normal or cool (Freitas, 1996). In this work, the data sources used were the SST and Pacific Ocean pressure differences presented by Wright (1989). These data were homogenized by Wright in order to take into account a possible change in measuring methods data density or station placement. The sea surface temperature anomalies are based on the difference between those to the long-term average. Positive values of this anomaly are related to values above average. The data were multiplied by 100, so that a value of +120, for example, corresponds to a temperature of +1.2 ° C above the average. The (Darwin - Tahiti) air pressure difference, hereafter DT, describes the pressure gradient between these Pacific endpoints and the so-called Southern Oscillation. During the "normal" years pressure at Darwin is smaller than the Tahiti, so DT has positive values meaning an inversion of the so-called Walker Circulation.

Regression Analysis and Conditioned Probability Tables

Various data combinations of correlation coefficients were computed for the studied pluviometric stations, for monthly, three months, six months, and total annual averages. This was done in order to establish which was the best correlation coefficient data set. For each station the rainfall exceedance probabilities corresponding to 33% and 67%were calculated'. These levels were used to classify the analyzed periods in dry, normal or wet. For SST anomalies limits -50 and +50, ie an anomaly of -0.5 ° C and +0.5 ° C, which also approximately correspond to 33% and 67% quantiles were chosen. This analysis was carried out for rainfall average values of MAM(-1), JJA(-1) and SON(-1) and anomalies SSTs (DJF the following year), ie to 9 and 6 months advance, respectively. Table1 shows the results for the Mombaçastation. The table show conditioned probabilities for rainfall categories (wet, normal and dry) against SSTs anomalies (cool, normal, warm). For this station, for example, there is an anomaly greater than 0.5 ° C in MAM(-1) which denotes a rainfall probability of about 54% of presenting (DJF) below the 33% quantile (dry) or a probability of 92% to provide a total precipitated below 67% quantile. For contingency diagrams and conditioned probabilities tables implementation on a forecast drought model using only Pacific Oceansea temperaturea check was performed in a forecast for Ceará state. In this test, probability tables of average values of all tables (stations) for the period of 9, 6 and 3 months before the period to be predicted (DJF) were implemented. Table 2 shows the results for the 6 months in advance period. It is assumed these tables are representative for the Ceará state.

Table 1. Conditioned Probability Table for JJA(-1) SST vs Precipitation at Mombaça (Ceará State)

JJA (-1)	Cool	Normal	Warm
DJF	SST (14 events)	SST (47 events)	SST (13 events)
Wet period	42 %	36 %	8 %
Normal period	29 %	34 %	38 %
Dry period	29 %	30 %	54 %

Warm SST: x > 50; Wet year:y > 820; Normal SST: -50 ≤ x ≤ 50; Normal year: 500 ≤ y ≤ 820; Cool SST:x < -50; Dry year:y < 500

ENSO years: 1911, 1914, 1918, 1923, 1925, 1930, 1932, 1939, 1941, 1951, 1953, 1957, 1965, 1969, 1971, 1976, 1982 (Rasmusson and Carpenter,1983)

Table 2. Conditioned Probability Table for Ceará State: JJA(-1) SSTs vs. DJF-Precipitation

JJA (-1)	Cool	Normal	Warm
DJF	SST	SST	SST
Wet period	31 %	39 %	12 %
Normal period	35 %	33 %	22 %
Dry period	34 %	28 %	66 %

Table 2 showsa 66% of a dry period (DJF) likelihood for SST indexes greater than +50 (i.e. +0,5ºC) In this circumstance, the probability associated with the dry and normal periods for a 6 month in advance forecast is found to be 88%. Forecasts based on JJA (-1) SST show that dry periods in DJF in the Ceará State can be predicted nearly six months in advance. A total of twelve values at six stations employed for validating for the years 1983 and 1984, eight were estimated as dry, corresponding to about 67%, in a conditioned probability table. Similarly, the eleven of a total of twelve were related to eight dry and three normal years, very close to the 88% value in the same table.

Artificial neural networks and machine learning techniques

Artificial Neural Networks provided a significant progress for systems theory and pattern recognition fields. Neural networks have a very flexible mathematical structure, being capable of non-linear relations identification and complex processes description. This name is given for models that replicate biological networks structures and performing, as the brain (Kosko, 1992). A neural network consists of a large number of elements, called neurons (cells, units), and a large number of connections (links), known as synapses. Each connection is associated with a weigh, which is intrinsically related to the network learning capacity. Thus, it is called an intelligent system, having, as a fundamental characteristic its learning capability. Different network topologies and various input data combinations (time annual, quarterly and monthly, and Atlantic and Pacific Oceans data) were analyzed (Figure 3).

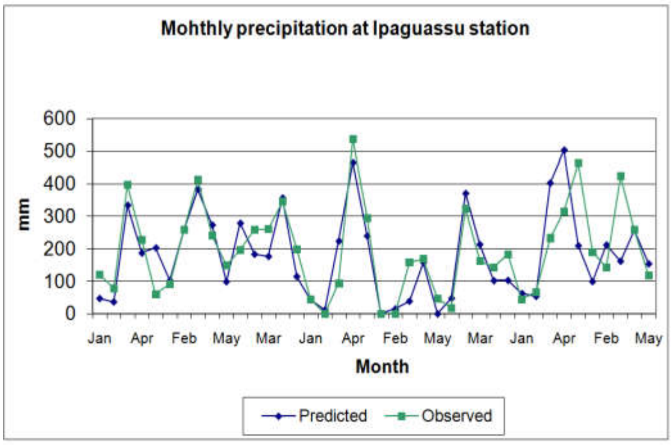

Figure 3. Predicted and observed monthly precipitation at Ipaguassu station (Ceará State), using the back propagation through time algorithm, without adaptative process

The primary advantage of this methodology lies in the use of advanced mathematical techniques, which allow to achieve a given level of accuracy and advance an estimate of the total to be precipitated or drained within a given region during the rainy season. This prognosis is valuable for optimizing reservoir operation, especially when coupled with flow generation models (Billib and Freitas, 1996). Two basic procedures were tested in each station: modeling their own rainfall series, and the use of SSTs Pacific and Atlantic oceans through neural networks. Then, the drought index was calculated for the thirty pluviometric stations chosen in Ceará state: the Lamb Rainfall Departure Index (LRDI) according Lamb *et al.* (1986) for the rainy semester (January-June) and correlated with the Atlantic SST. Machine learning techniques have also been tested for drought index prediction and also for streamflow prediction (Belayneh and Adamoswski, 2013; Raha and Gayen, 2019; Freitas, 2019).

Drought monitoring

Drought periods monitoring can be accomplished through the use of indices, the so-called drought indices. Based on them, we can develop a drought characteristic monitoring system, as well as the different measures to be affected in accordance with the values of these parameters. The most known and widely used for the investigation of the spatial and temporal distribution of drought periods is the determination of some drought index. This index can usually be defined as a value which represents the cumulative effect caused by a long water deficit period (Freitas, 2005). Due to the difficulty of having a single drought phenomenon definition, drought index determination is also problematic. Drought severity is usually expressed as a function of the mean value of one or several climate parameters. The most usual drought indexes express the total precipitation in a given region as a known average data percentage. Thus, one can compare the current value with the average value of weekly, monthly, semiannual or annual series.

Rainfall Anomaly Index (RAI)

The first index that was incorporated into the Drought Management System - SIGES in order to make it possible to compare rainfall deviations related to the normal conditions of various regions is called the Rainfall Anomaly Index (RAI), described by Rooy (1965) and pioneered in Brazil by Freitas (2005). After this, numerous works showed its applicability in the Brazilian territory (Lima *et al.,* 2016; Freitas, 2016; Martorano *et al.,* 2017) and other countries (Raha and Gayen, 2019). In those studies, it was verified that the Rain Anomaly Index functioned as a good instrument for the study of seasonal precipitation. Through this monitoring can generate predictions about the regional climatological variation. Figure 4 shows an example of the application of this index to 185 pluviometric stations in the Piauí state. It is easy to recognize 1974 as a wet year and 1993 as a typically dry year for almost all stations analyzed.

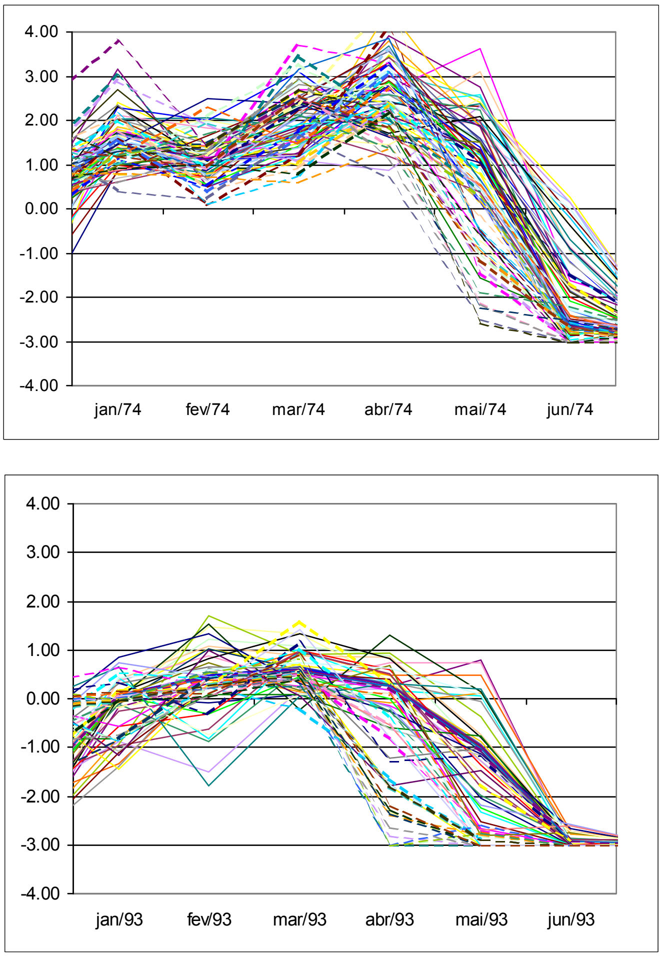

Figure 4. Rainfall Anomaly Index (RAI) for 185 Piauí State pluviometric stations, applied to a wet year (1974) and to a dry year (1993)

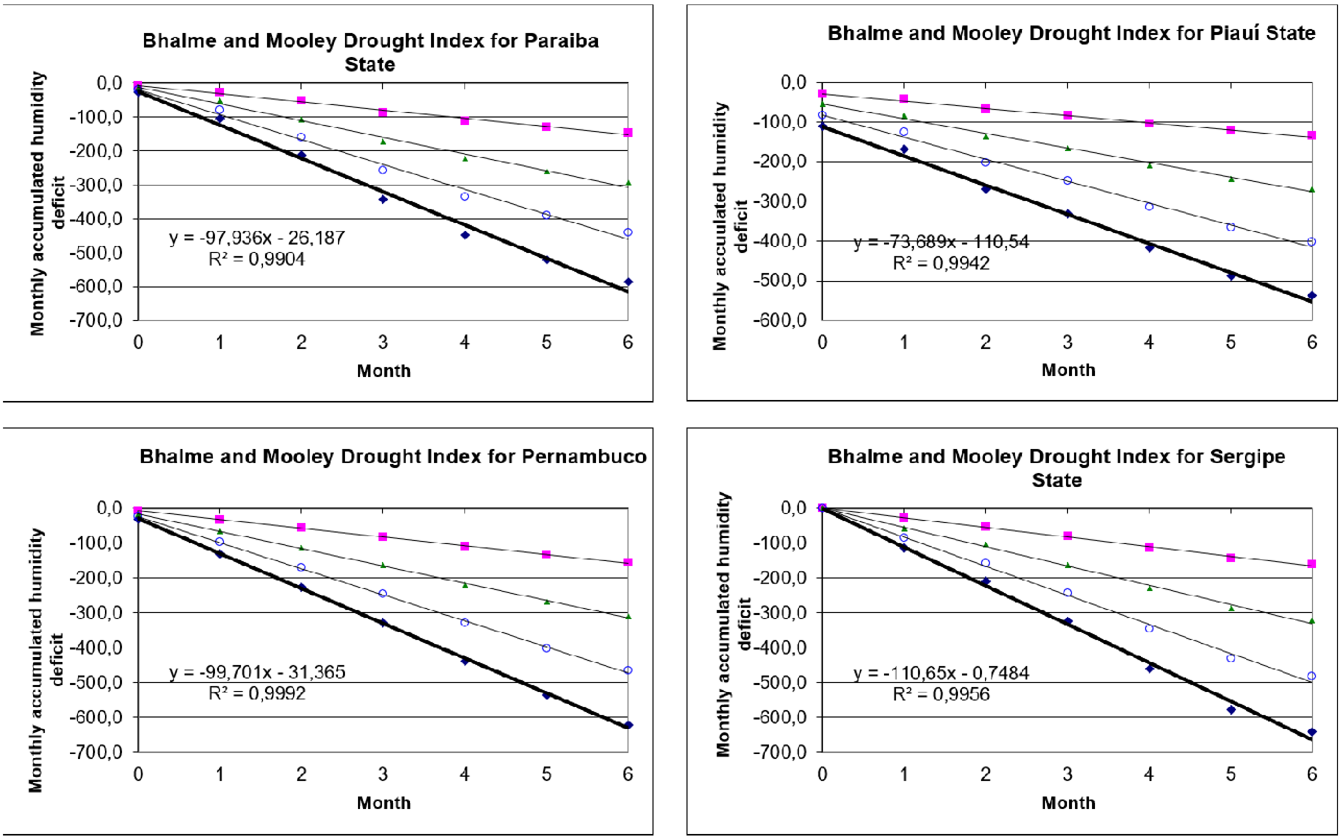

Figure 5. Bhalme & Mooley Drought Index (BMDI) for Paraiba, PiauíPernambuco and Sergipe States

Bhalme and Mooley Drought Index (BMDI)

Palmer (1965) presented a water balance procedure, for the semi-arid region of western Kansas State and the sub-humid region of Iowa, USA later known as the Palmer Drought Severity Index (PDSI). The PDSI is calculated based on evapotranspiration, infiltration, runoff and other data, expressing a measure for the accumulated difference between the normal precipitation and the precipitation necessary for evaporation. This analysis is done on a weekly or monthly basis. This procedure gives out an index that ranges from -4 (extreme drought), through zero (normal) to +4 (very humid periods). Several authors (Alley, 1985; Guttman, 1991) demonstrated that the PDSI was not a good humid condition indicator, particularly during dry periods. Another PDSI disadvantage is that the regularization of the flow surface is not considered. Bhalme and Mooley (1980) also pointed out the same problems for tropical regions of India. They then proposed a modification of the original content, in order to incorporate the climatic conditions prevailing in India. This index was known as Bhalme and Mooley Drought Index (BMDI). Figure 5 shows the application of this index for the Paraiba, Piauí, Pernambuco and Sergipe states. Freitas (2005) presented the application of BMDI for Ceará State. Since this index present both positive and negative values it can be used in evaluating periods of droughts and floods. The values of current, monthly, accumulated during the crops growth or the rainy season (January to June) BMDI can then be compared with historical values in the region, so as to have a permanent control of the humid condition.

Lamb Rainfall Departure Index (LRDI)

The calculation of this ratio (Lamb *et al.,* 1986) consists of a normalization procedure, through which average deviations of precipitation of various stations in a given region are grouped to determine a unique index. A major advantage of this method is that all the precipitation series, which usually have many gaps, can be used in determining a regional index. Figure 2 shows the result of the use of this methodology to pluviometric stations analyzed in the Cearástate.

Reservoir operation optimization using climate information

Among the various SIGES applications, we will report now those related to shortage impact mitigation based on forecasting and monitoring information for these periods. In semiarid regions with high evaporation rates the water resources manager often faces the problem of determining minimum water losses conditions for surface reservoir operation, considering different uses, their priorities shortages or rationing situations. Silveira and Freitas (2004) deal with that considering two options: firstly, the conventionally used model, in which the total amount of water is assured for the more prioritary sectors while those with lower priority are being exhausted. In the second, each user´s quota is divided into two parts: being exhausted first, the part that corresponds to the surplus of the balance of each economic sector, ie, the region above its equilibrium point, moving then to ration the second part of the quota. Thus, it is seeked to establish a criterion to minimize the possibility of breakage of entire sectors of the economy (optimal hedging rules and hydrological status methods). Another method for dealing with this problem is performed using the so-called Risk Aversion Curve (Gondim Filho *et al.,* 2005). In many basins, due to lack of fluviometric data, it is often necessary to obtain a series of influent flow to the reservoir through the use of rainfall-runoff or synthetic stream flow generation models. For the generation of synthetic flowrates in intermittent rivers typical of semiarid regions, Freitas (1995, 2010) presented the SAGE system -

Stochastische Abfluss G Enerierungsmodelle, consisting of the following models: i) PAR-Model (Thomas / Fiering) with modification of Clarke, ii) PAR-Model (Thomas / Fiering) with transformation Matalas, iii) Two-tier model (PAR (1) / AR (1) with log-gamma distribution), iv) Two-tier model (PAR (1) / AR (1) with log-normal distribution), v) Two-tier model (PAR (1) / GAR (1) of Fernandez and Salas; Fragment method-AR (1) log-gamma distribution, vi) Fragment method-AR (1) with log-normal distribution; vii) Fragment-GAR (1); viii) Disaggregation model / AR (1) by Valencia and Schaake. Later, Freitas (2010) presented applications of the model ARRF (Alternating Renewal Reward - Fragment) to various basins in northeastern Brazil.

Conclusions and Recommendations

The proposed models offer a practical approach for forecasting rainfall between 6 and 3 months in advance of the rainy season. Using the methods described above for predicting droughts, and various indexes of drought, combined with models of flow generation (Freitas, 1995), opens a new perspective in the management and optimization of water resources systems in semiarid regions, as the Northeast of Brazil. The aim of the correlation analysis was to verify the correlation degree between El Niño and drought incidence in northeast Brazil. So data were initially grouped in various ways, for example, averaged for three (3) and six (6) months and later correlated with the index of ENSO, i.e., El Niño (SSTs) and Southern Oscillation (SOIs). In northeastern Brazil, particularly in Piauí and Ceará states, extreme droughts often occur whenever there happens the phenomenon known as ENSO. The teleconnections between ENSO indices (Pacific) and interannual rainfall in these states can be used in drought forecast models, based on conditional probability tables and neural networks. These predictions once incorporated into rainfall-runoff models and stream flow generation models can contribute for the reservoir management and operation optimization in this region. SIGES have been of great importance as a subside to mitigatory actions, specially the so-called no-regret actions for the current extreme drought period (2012-2019), as demonstrated on Rusteberg and Freitas (2018).

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Conflict of interest: The authors declare no conflicts of interest.

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