Drought in Costa Rica: temporal and spatial behaviour, trends and the relationship to atmospheric circulation patterns

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Abstract The temporal and spatial behaviour of droughts in Costa Rica has been studied applying the threshold level approach to 17 streamflow stations for the common period 1973–2003. Drought indices such as drought duration, deficit volume (severity) and the number of droughts (frequency) were determined utilizing a constant non-seasonal Q_{90} and seasonal Q_{70} exceedence percentile from a flow duration curve. Temporal drought characteristics were generally of long duration and low deficit volume in the dry season and droughts of short duration and high deficit volume tend to cluster in the wet season. This could be a feature of the threshold, or the standardization procedure or the seasonality of the flow regime. Spatial drought characteristics show distinctive regional patterns in terms of variability indices and drought risk. The non-parametric Mann-Kendall trend test shows just one significant ($\alpha = 0.05$) positive result in terms of historic trends in increased severity and frequency (at the Northern Zone). Although the majority of test results are non-significant, a clear spatial pattern of positive and negative trends can be seen. The link between atmospheric circulation patterns and regional streamflow drought point towards regional patterns of a direct atmospheric-control (Pearson $r > 0.5$).

Key words drought; threshold level method; drought pattern; Mann-Kendall Test; atmospheric circulation; ENSO; El Niño

INTRODUCTION

Drought in the tropics is not a rare or random event, but a normal recurrent feature of the climate. Many studies attempt to regionally associate and quantify dry periods with the warm El Niño phase (Piechota & Dracup, 1996; Waylen *et al.*, 1998, Dettinger *et al.*, 2000), but few efforts have been made to generally analyse temporal and spatial drought behaviour in the region of Costa Rica. However, persisting over months and seasons, drought can affect large areas and cause tremendous social hazard, environmental damage and economic loss.

Recent droughts in Costa Rica have highlighted not only the vulnerability of the Costa Rican economy (agriculture), but also the threat to the local population of shortages in water supply. The unusually dry years of the 1997–1998 El Niño event in Central America led to losses of US$ 32.8 in Costa Rican agriculture alone (CEPAL, 2005). Since the early 1970s, scarcely a decade goes by without at least one region of the country being affected by drought. This study was carried out to improve the understanding of drought characteristics in Costa Rica.

STUDY AREA

The area under investigation, Costa Rica, is located in the south of the Isthmus of Central America with political borders to Nicaragua in the north and Panama in the south. It stretches from 8°00′ south to 11°15′ northern latitude and from 82°30′ east to 86°00′ western longitude with an area of 51 110 km^2 (Fig. 1). With two coastlines, one in the east (Caribbean Sea) and the other in the west (Pacific Ocean) marking its natural borders, the region covers six distinct, but homogeneous land units varying in climate, geology and hydrology (the North Pacific region, the Northern Zone, the Caribbean, the Central Pacific region, the Central Valley and the South Pacific region). Streamflow regimes are, according to Guilcher (1979) and Silva (1991), of a simple pluvial character showing a strong seasonality (low and high flow season) but due to precipitation variability of a regular or irregular type. Comparisons of regimes assigned to geographical land units of comparable climatic properties show similar characteristics and support this regionalization.

The national electricity company (ICE) provided the hydrological data. Seventeen stream gauges all with data from 1973–2003 and with natural flow characteristics were selected (Fig. 1). The size of the basins chosen for this study varies between 200 and 4767 km^2. Drought properties have been calculated for this subset of Costa Rican stations to provide a good regional coverage across Costa Rica in order to derive temporal and spatial drought patterns.

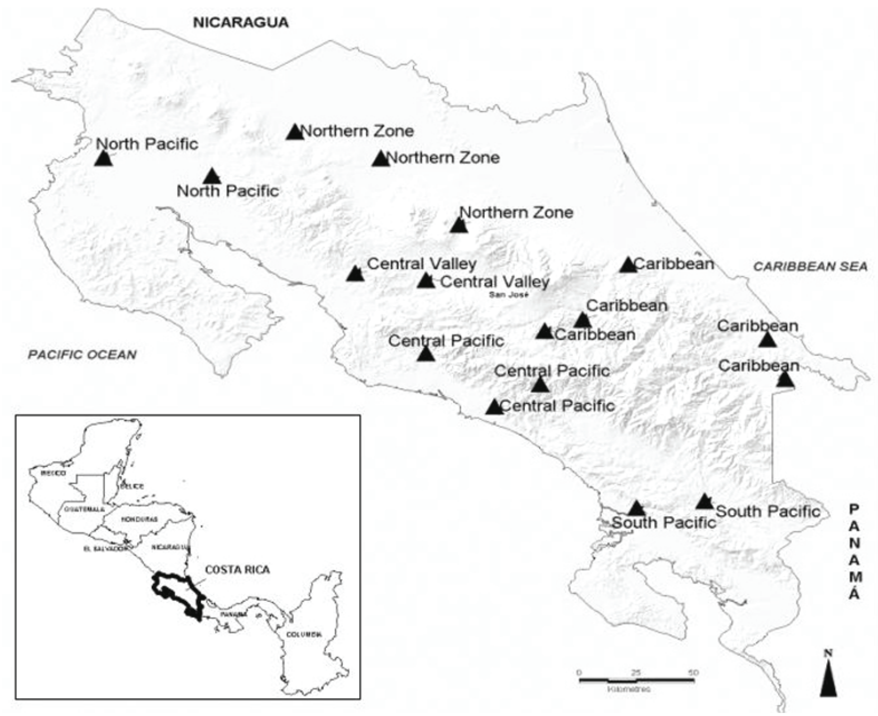

Fig. 1 Streamflow gauges across Costa Rica according to distinct climatic regions.

DROUGHT EVENT DEFINITION

Hydrological drought events can be defined by the threshold level method using a particular discharge value (in this study Q_{90} and Q_{70}), from the flow duration curve. The strong seasonality of tropical flow regimes required the comparison of a constant non-seasonal (hydrological year) with a constant seasonal (low and high flow season) threshold level. Drought events were defined in terms of duration *d* (days), deficit volume s (1000 m^3) and the number of droughts (–) occurring. Annual maximum and accumulated drought indices in terms of duration (AMD, ACD) and severity (AMV, ACV) for the typical low and high flow seasonality were calculated. These indices were derived using a constant non-seasonal (Q_{90}) threshold level and using constant seasonal thresholds (Q_{70}) for high (HF) and low flow (LF) periods respectively.

TEMPORAL BEHAVIOUR OF DROUGHT

Temporal drought behaviour was investigated by comparing averages of distinct drought indices such as the annual maximum duration (AMD in days), the annual maximum deficit volume (AMV in 1000 seconds due to a normalization process by mean flow) and the number of droughts (ND) for the common period 1973–2003. Table 1 shows the results of representative streamgauges for regions with a similar climate. The average annual maximum indices (mean AMD, AMV and ND) indicate that a generalized temporal drought pattern in terms of droughts of long duration and low deficit volume span the dry season, and droughts of short duration and high deficit volume tend to cluster in the wet season, which is e.g. reflected at the North Pacific station “Guardia”. Here the mean HF Q_{70} is 17.9 days and the mean LF Q_{70} AMD is 39.2 days. The severity index AMV shows four exceptions out of a total of 17 stations, e. g. the Guardia station has a LF Q_{70} AMV of 220, whereas the HF Q_{70} AMV is 180.6. In terms of the ND index 50% follow the concept of clustering in the high flow season (HF). The clustering of high deficit volumes could also be a feature of the threshold, or the standardization procedure or the strong seasonality of the flow regime.

SPATIAL BEHAVIOUR OF DROUGHT

A variability index was developed to assess how sensitive a basin is to drought, because, the higher the variability, the more sensitive the river flows are to extreme droughts (Demuth & Heinrich, 1997). An increase in deviation from the mean drought index, such as AMD or AMV,

Table 1 Constant drought indices of one representative station according to climatic regions.

Climatic region	Station	Threshold	Mean AMD (days)	Mean AMV (1000 s)	Mean ND
Northern Zone	Guatuso	Q_{90} annual	35.6	127.1	1.2
		Q_{70} LF	40.5	194.1	1.3
		Q_{70} HF	20.1	367.9	2.7
North Pacific	Guardía	Q_{90} annual	32.2	142.3	0.8
		Q_{70} LF	39.2	220.0	0.9
		Q_{70} HF	17.9	180.6	1.7
Central Valley	Tacares	Q_{90} annual	27.5	132.9	1.2
		Q_{70} LF	42.6	252.9	1.3
		Q_{70} HF	23.4	384.0	1.0
Central Pacific	Londres	Q_{90} annual	28.3	94.7	1.4
		Q_{70} LF	28.3	94.7	1.4
		Q_{70} HF	15.3	275.3	1.2
South Pacific	Caracucho	Q_{90} annual	25.9	94.3	1.6
		Q_{70} LF	34.4	138.9	1.7
		Q_{70} HF	28.0	571.8	1.8
Caribbean	Pandora	Q_{90} annual	20.9	104.5	1.9
		Q_{70} LF	34.1	267.8	1.9
		Q_{70} HF	18.3	420.2	2.7

results in higher variability indices, expressed as the ratio of standard deviation to either mean duration or mean deficit volume in percent (%). The calculation was computed for the Q_{90} non-seasonal and Q_{70} seasonal (low and high flow season) AMD and AMV series. Zero drought years were taken into account to obtain the most real spatial data. Results are presented in Fig. 2, which shows the seasonal (HF, LF Q_{70}) variability coefficients for the Annual Maximum Deficit Volumes (AMV). Low variability (<100%) is reflected by a smaller sized clear coloured triangular, while the highest variability (>130%) is assigned by a darker sign.

The seasonal indices vary considerably in magnitude and range from 71 to 179% (Fig. 2). The lowest value was obtained for the low flow (LF) seasonal AMV at the Guatuso station, Northern Zone, and the highest value at station Rancho Rey, North Pacific, for the high flow variability AMV index. The high flow seasonal variability's (HF) principally reveal a higher susceptibility (mean variability: 120% HF AMV – 104% LF AMV) to drought than during the dry season. In general, a clear division between the Pacific and Caribbean drainage basin can be seen for the high flow season AMV. Figure 2 reveals the Central Valley, the North and Central Pacific as the regions most afflicted by extreme droughts, while the western part of the Northern Zone and the Caribbean show the lowest.

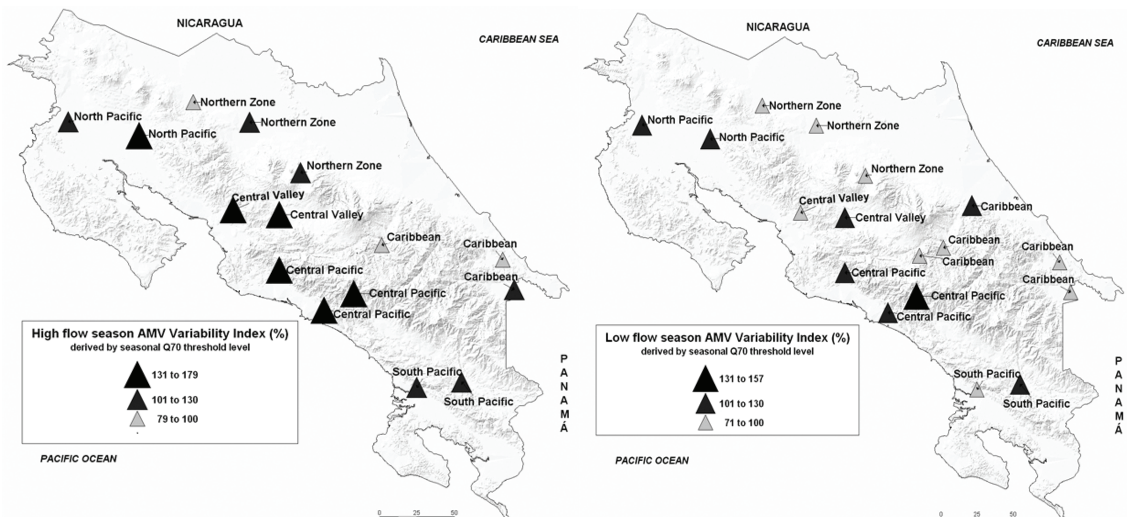

Fig. 2 Regionalized variability indices (%) of seasonal AMVs (HF-left, LF-right) for the period 1973–2003.

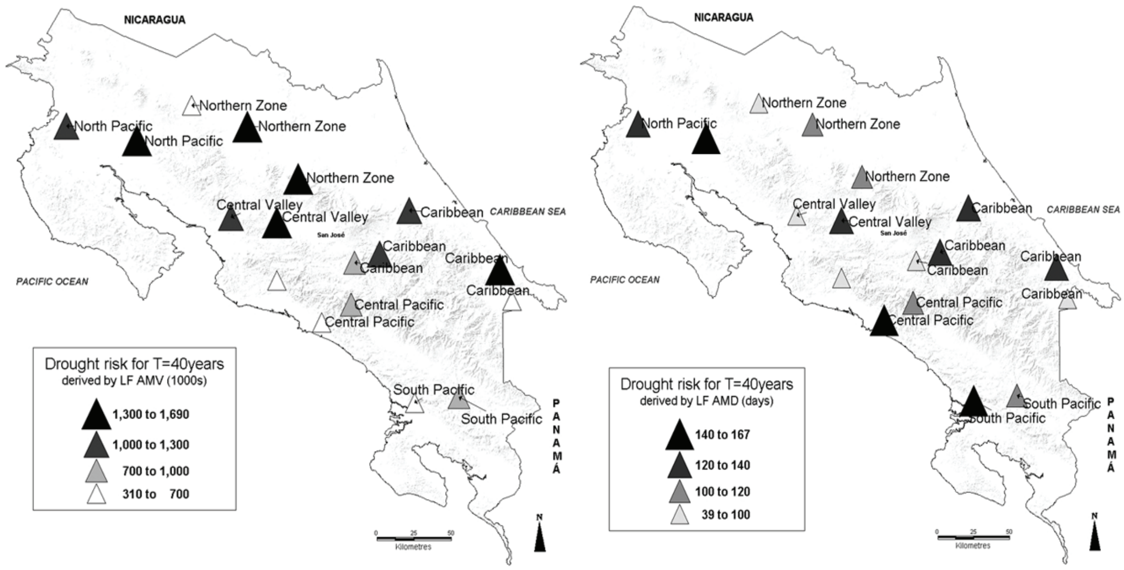

Fig. 3 Estimated 40-year return periods (*T*) for seasonal (LF) AMVs (left) in 1000s and LF AMDs in days (right).

The definition of risk used in this study is that developed by Tallaksen & van Lanen (2004) and is equal to the probability of non-exceedence of a certain minimum level (threshold level) within a certain *T*-year period. The cumulative distribution function (cdf) of the largest event within one year or season from a partial duration series (PDS) of drought events was derived.

The methodology presented by Zelenhasic & Salvai (1987) for describing and analysing the stochastic process of streamflow droughts was adapted using the program NIZOWKA (Jakubowski & Radczuk, 2004) to estimate drought characteristics. The distribution that fitted drought durations and deficit volumes best was the Poisson distribution for the number of droughts and the Lognormal and Pearson distribution for duration. The Poisson distribution was chosen for the number of events and the Generalized Pareto distribution for estimating magnitudes of the deficit volume extreme statistics. The calculated return periods (T – 10, 20 and 40 years) for each gauging station and drought index are regionalized across the study area to gain a general picture of the stations, which run most risk of being affected by severe droughts.

Figure 3 shows the spatial 40-year return periods for the low flow season (LF) Q_{70} AMVs (left panel) and the LF Q_{70} AMDs (right panel). The North Pacific region, the northern Caribbean and several other basins in the Central Valley (Tacares: estimated extreme duration of 169 days), the Central (station Providencia) and South Pacific region (station Palmar) (Fig. 3) are of high drought risk. For drought duration (right panel), the deficit volume characteristics (left panel) indicate a clear north–south division. What is in agreement between the two indices is the high drought risk for the North Pacific and the Caribbean. With one exception (station Guatuso in the Northern Zone) the north of Costa Rica runs more risk of experiencing drought events during the low flow season.

TREND ANALYSIS

Trends in Costa Rican drought series were analysed by conducting the non-parametric rank based Mann-Kendall test (Hisdal *et al.*, 2001). The test was performed on three drought parameters (AMD, AMV and ND) derived with a constant non-seasonal threshold of Q_{90}, applying a two-sided test with a five percent (α = 0.05) level of significance. The results were assessed by mapping the spatial variability of the trends. Figure 4 shows the trend statistics for the Mann-Kendall test results on the AMV for each station. The stations exhibiting positive or negative trends tend to show typical spatial patterns. The Central Pacific and Central Valley react identically in their trend characteristics. The most distinctive Costa Rican region, where drought severity significantly increased is the western part of the Northern Zone. There a significant increasing trend towards more severe and more frequent droughts could be seen.

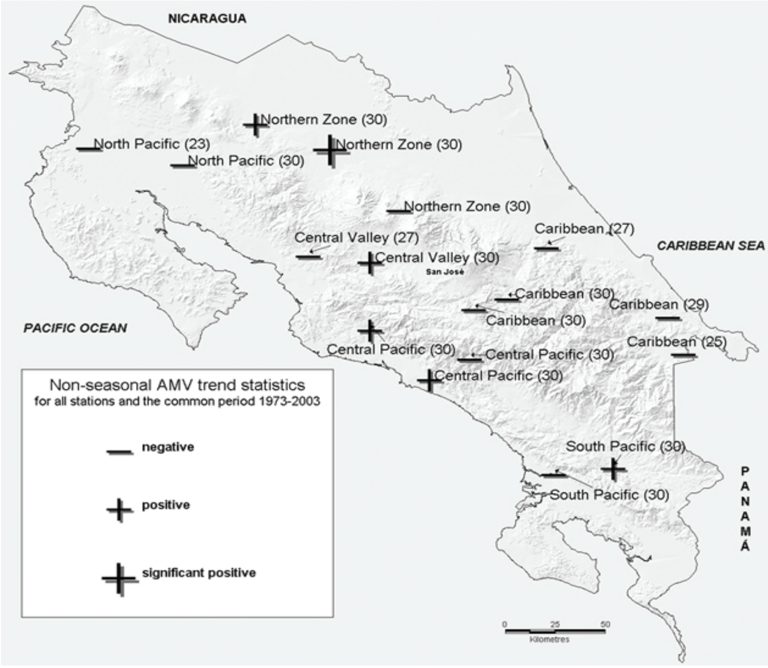

Fig. 4 Trends in AMV drought series of all stations for the period 1973–2003.

Stations with trends towards increased drought severity are clustered in the Central Pacific region, while stations with trends towards decreased drought severity are situated in the Central Valley region. The Caribbean and the North Pacific region exhibit in terms of drought severity a contradictory picture. There, some stations point at a trend towards decreasing severity, despite surrounding stations tending to increase drought severity.

LINKING ATMOSPHERIC CIRCULATION PATTERNS TO REGIONAL STREAMFLOW DROUGHT

To study the influence of atmospheric circulation on regional streamflow drought several aspects were investigated such as a correlation analysis using Pearson correlation coefficients. The statistical pre-processing of the data included the test of autocorrelation, linearity and normal distribution of the indices applied. Drought anomaly indices (ACD, ACV) are according to the pre-defined seasonality (high and low flow season) averaged and adopted for a linear correlation study with ENSO signals (SOI, SST, etc.).

The different seasonal drought anomaly indices (HF, LF ACV and ACD) show a similar relation with the sea surface temperature index (SST). Therefore, it was considered sufficient to concentrate on the spatial interpretation of just one anomaly index (HF ACV). This generally correlates (positively) with the Pacific drainage basin with the SST-ENSO signal.

The main active El Niño phase has more significant correlations for the high flow season. The Northern Zone shows indifference for the SST signal throughout the year and ENSO is considered not to be a major effect on drought behaviour in this region. The South Pacific shows high correlations with the SST index without seasonality and is the region of Costa Rica most directly affected by the El Niño oscillation.

CONCLUSIONS

Seventeen daily discharge series were used to define drought events and obtain a dataset of drought parameters indicating comparable extreme dry periods across Costa Rica’s principal climatic regions, physiographic characteristics and flow regimes. Typical temporal and spatial patterns could be found and the seasonality of Costa Rican streamflow droughts described, but inter- and within-season droughts vary considerably. The spatial behaviour of drought also follows specific patterns and to improve our understanding of drought development and drought processes an improved streamflow data resolution and regionalization methods are required.

Thirty years of data can not be considered as sufficient to fully address the question of whether streamflow drought has become more severe or frequent, due to the narrow time window. Although for Costa Rica as a whole no significant trends could be found, clear spatial patterns can be seen as a result of the trend analysis carried out in this study. Costa Rican streamflow exhibits significant correlations ($\alpha = 0.1$ of $r > 0.5$) between atmospheric circulation patterns (ENSO) and seasonal streamflow anomaly indices (ACD, ACV) with a time lag of a maximum of one year. The Pacific regions significantly interrelate with the Southern Pacific Oscillation, which proves to be an important influence on climate variability affecting regional drought development.

These pronounced, direct effects of climate variability on the hydrological cycle have the potential to form the basis of a regional drought-forecasting model. This statistical approach could provide useful long-range hydrological information for improving the sustainability of water resources in the region.

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