Institut für Hydrologie
der Albert-Ludwigs-Universität Freiburg i.Br.

Temporal and Spatial Variability of Drought Indices in Costa Rica

Christian Birkel

Diplomarbeit unter Leitung von Prof. Dr. S. Demuth
Freiburg i.Br., Juli 2005

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Abbreviations

ACD	Annual cumulated duration of all drought events (days)
ACV	Annual cumulated deficit volume (s)
AMD	Annual maximum drought duration (days)
AMIGO	FRIEND working group for Central America and the Caribbean
AMV	Annual maximum deficit volume (s)
ARIDE	Assessment of the regional impact of drought in Europe
AyA	Aguas y Alcantarillos (Costa Rican water supply Company)
BFI	Base Flow Index (-)
CEH	Centre for Ecology & Hydrology
CEPAL	Economic Commission for Latin America and the Caribbean
CEPREDENAC	Coordination Centre for natural disaster prevention in Central America
cdf	cumulative distribution function
CIGEFI	Centre of Geophysical Investigation
CORECA	Regional Council for Agricultural Cooperation
CRRH	Comité Regional de Recursos Hídricos
EEA	European Environment Agency
ENSO	El Niño-Southern Oscillation
EWA	European Water Archive
fdc	flow duration curve
FRIEND	Flow Regimes from International Network Data
GIS	Geographical Information System
GRDC	Global Runoff Data Centre
HF	high flow season
IC	Inter-event criteria (days)
ICE	Instituto Costarricense de Electricidad
IDW	Inverse Distance Weighting method
IMN	Instituto Meteorologico Nacional
IPCC	Intergovernmental Panel on Climate Change
ITCZ	Inner tropical convergence zone
LF	low flow season
MA	Moving average criterion (days)
MAG	Ministry of Agriculture and Livestock

MAM	Mean Annual Minimum flow (m^3/s)
MK	Mann-Kendall trend statistic (-)
MSLP	Mean sea level pressure (hPa)
NAO	North Atlantic Oscillation
NASA	National Aeronautics and Space Administration
ND	Number of drought events per year (-)
NDMC	National Drought Mitigation Centre
NOAA	National Oceanic and Atmospheric Administration
NUMEROSA	data base of CRRH
PDS	Partial Duration Series
SLP	Sea Level Pressure (hPa)
SPA	Sequent Peak Algorithm
SOI	Southern Oscillation Index (-)
SST	Sea Surface Temperature departure (-)
UCR	University of Costa Rica
USGS	United States Geological Survey

Symbols

α	significance level (-)
σ	minimum drought deficit volume (1000 m³)
μ_i	mean annual flow for year i (m³/s)
μ_j	mean annual flow for year j (m³/s)
D	difference between ranks of two variables (-)
D_{ij}	seasonal drought anomaly index for year i and season j (-)
d_i	drought duration (days)
d_{min}	minimum drought duration (days)
E	expectation (-)
HHQ	absolute highest discharge (m³/s)
Mp	monthly mean precipitation (mm)
MQ	mean discharge (m³/s)
Mq	mean yield (l/s*km^2)
N	number of subjects (-)
NNQ	absolute lowest discharge (m³/s)
p	exceedance probability (%)
P	precipitation anomaly (-)
Pr	probability (%)
Q	discharge (m³/s)
q_o	threshold level (streamflow in m³/s)
Q_{70}	flow exceeded for 70% of the time (rep. Q_{90}, Q_{80} etc.) (m³/s)
r	Pearson product moment correlation coefficient (-)
r (k)	autocorrelation coefficient (-)
r (d)	cross-correlation coefficient
r_s	Spearman correlation coefficient (-)
R^2	coefficient of determination (-)
s_i	drought severity of event i (1000 m³)
sgn	signum function (-)
S	standard deviation (-)
t	time (s)
t_i	inter-event time criterion (days)
T	return period (years)
Var	variance (-)

x	real variable (-)
X	random variable (-)
y	variable (-)
z_i	inter-event excess volume (1000 m^3)
Z_k	time series (-)

Abstract

The following thesis “Temporal and spatial behaviour of drought indices in Costa Rica” realises a qualitative and quantitative characterisation of general drought patterns at a national scale. The principal aim of this study is to determine temporal and spatial drought behaviour in Costa Rica by translating the threshold level approach to climatologic characteristics of the Neotropics.

The research region, located in Central America is characterised by a monsoon-type climate. Strong seasonality in flow regimes implies the use of a “constant seasonal threshold level for high and low flow season, respectively to derive drought indices from long-term records of daily discharge. Annual maximum and cumulated durations (AMD, ACD), annual maximum and cumulated deficit volumes (AMV, ACV), as well as the number of droughts per year (ND) were used to establish typical drought behaviour.

Temporal drought characteristics are described by overall drought indices in order to evaluate general dry or wet years over the thirty-year period of record from 1973 to 2003. Sequences of dry years indicate persistence in the hydrological system, which is discussed by derived autocorrelation coefficients. This analysis revealed in between the 95 % confidence interval a non-persistent behaviour. Furthermore, to satisfactorily describe temporal behaviour of regional droughts, seasonal occurrence is an important issue. The precipitation and runoff patterns of Costa Rica are characterised by high interseasonal variability.

Costa Rica generally exhibits two distinct types of streamflow droughts:

- Most severe droughts of long duration and low deficit volumes span dry or low flow season.
- During wet or high flow season minor droughts of short duration and high deficit volumes tend to cluster.

In fact, the high flow season drought phenomena can be considered important for later drought development in some particular regions and can not be neglected in further spatial drought study.

Spatial drought behaviour can be analysed by regional distributions of maximum drought indices, variability indices, seasonal anomaly indices and by defining drought risk. These indices were mapped to visually display regional drought and to improve the understanding of spatial drought patterns.
Drought indices show distinctive regional patterns. The period of record maximum index tends to occur in the same region as drought centre. The Pacific watershed can be clearly separated from the Atlantic contributory area, where severe droughts seem to appear in a decadal pattern.

Regions, which are more afflicted by maximum events, can be determined by variability drought indices. This index reveals the most affected regions among all seasons as the North Pacific, the Central Pacific and parts of the Caribbean. The variability index shows seasonality and presents differences in magnitudes of variability between high and low flow periods. Higher variability's during wet season indicate the possibility for more severe events than for dry season, because during dry season drought is a natural climatic experience in most drought-proned regions.

Anomaly indices exactly distinguish between the severe droughts and a natural drought to better assess drought severity. A map of the latter indices over a sequence of dry years (1991-1995) reveals a certain "drought movement" across different physiographical regions, which normally are not considered to be susceptible to drought.

Drought risk, defined as non-exceedance probabilities from partial duration series of drought indices (AMD, AMV), determined the North of Costa Rica (including one exception) to run more risk experiencing severe drought events with a return period of 40 years than the rest of the country.

Although a trend analysis realised with the non-parametric Mann-Kendall trend test could not reveal a general significant positive or negative trend in drought series (AMD, AMV and ND) for Costa Rica as a whole, for the common period clear regional patterns can be found in terms of drought frequency and severity.

The linkage of atmospheric circulation patterns to regional streamflow droughts in order to determine causes for drought in Costa Rica was a further aim of this thesis. A correlation analysis provides great potential to reveal a strong dependence of regional drought on oceanic-atmospheric patterns according to statistical assumptions like no auto-correlation, linearity and normal-distribution. Significant (α = 0,1) Pearson correlation coefficients (r > 0,5) for Pacific Ocean sea surface temperature departures (SST 3.0) and drought indices at the Pacific Vertient could be found. The Atlantic Oscillation Index and drought indices at the Atlantic Vertient remarkably show a strong relation. In Costa Rica, regional streamflow drought develops at different scales through the hydrological cycle.

Global and regional circulation patterns determine natural climate variability, which is modified by physiographic catchment's characteristics. According to a cross-correlation study, the temporal scale of streamflow drought development seems to be limited to the next recharge season, which is considered to be high flow season. In other words, climate variability is assumed to directly affect the region rather than to persist over several years.

The results of this study encourage the development of a long-term drought forecast model to provide important information on regional streamflow drought for preventive steps implemented in emergency plans of action for sustainable water resources management.

Keywords:

streamflow drought	atmospheric circulation patterns
Neotropics	correlation analysis
drought indices	ENSO
threshold level	El Niño

Zusammenfassung

Die vorliegende Diplomarbeit “Temporal and spatial behaviour of drought indices in Costa Rica” realisiert eine qualitative und quantitative Charakterisierung genereller Dürremuster auf nationaler Ebene. Die Zielsetzung dieser Studie ist, wie der Titel der Diplomarbeit besagt, zeitliche und räumliche Dürremuster durch Übertragung der Schwellenwertmethode auf klimatische und räumliche Besonderheiten Costa Ricas, zu erfassen.

Die Testregion Costa Rica befindet sich in Zentralamerika und ist von einem Monsun-artigen Klima und einer starken Saisonalität im Abflussregime geprägt. Dies implizierte die Anwendung eines konstanten saisonalen Schwellenwertes für Hoch- und Niedrigwassersaison zur Berechnung von Dürreindizes aus langjährigen täglichen Abflussreihen. Jährliche, maximale und kumulierte Dürredauern (AMD, ACD) sowie jährliche, maximale und kumulierte Defizitvolumina (AMV, ACV) und die Anzahl auftretender Dürren pro Jahr (ND) wurden als Dürreindizes verwendet, um ein typisches Verhalten von hydrologischen Dürren zu generalisieren.

Zeitliche Dürrecharakteristika können in erster Linie über sogenannte Overall Dürreindizes beschrieben werden, welche als Summe über die gesamte dreißig-jährige Zeitreihe (1973 - 2003) aller Stationen generelle Trocken- und Nassjahre evaluieren. Sequenzen von Trockenjahren lassen auf Persistenz im hydrologischen System schließen, welche über die Berechnung von Autokorrelationskoeffizienten diskutiert werden kann.

Diese Analyse lässt innerhalb der 95 % Konfidenzintervalle keine Persistenz im Verhalten der Overall Dürreindizes erkennen. Für eine zufriedenstellende Beschreibung zeitlicher Muster regionaler Dürre soll weiterhin deren Saisonalität genauer untersucht werden. Das Niederschlags- und Abflussverhalten Costa Ricas ist von intersaisonaler Variabilität gekennzeichnet. Dies resultiert in ausgeprägten Niedrig- und Hochwasserperioden während eines hydrologischen Jahres.

Generell gesehen, zeigt Costa Rica zwei verschiedene Arten von hydrologischer Dürre:

- Die meisten schweren Dürren von langer Dauer und geringen Defizitvolumina treten über die Trockenzeit auf.
- Dürren von kürzerer Dauer und großen Defizitvolumina häufen sich in der Regenzeit.

Tatsächlich kann das Dürrephänomen zur Hochwassersaison für manche Regionen als maßgeblich beteiligt an der weiteren, intersaisonalen Entwicklung einer Dürre gesehen werden.

Räumliche Dürremuster können durch die regionale Verteilung von Maximal-, Variabilitäts- und Anomalitätsindizes und über ein definiertes Dürrerisiko beschrieben werden. Die genannten Indizes werden für ein besseres räumliches Verständnis in Karten übertragen.
Dürreindizes zeigen verschiedene räumliche Muster. Die Maximalindizes für das gesamte Zeitfenster tendieren zu regionalem Auftreten und fungieren dabei als Dürrezentren. Weiterhin kann beobachtet werden, dass das Pazifische Einzugsgebiet durch dekadisch auftretende Dürren räumlich klar vom Atlantischen getrennt wird. Mittels in Karten dargestellten Variabilitätsindizes können Regionen, die besonders von Schwerstereignissen betroffen sind, bestimmt werden. Diese lassen erkennen, daß die Regionen des Nordpazifiks, des Zentralpazifiks und Teile der Karibik ganzjährig am stärksten betroffen sind. Es zeigen sich jedoch saisonale, quantitative Unterschiede der Variabilitäten, in der Art, dass eine höhere Variabilität in der Regenzeit zu schwereren Dürreereignissen führen kann als die direkte Variabilität in der Trockenzeit ohnehin erwarten lässt.

Anomalitätsindizes setzen an diesem Punkt an und unterscheiden ein Extremereignis von der saisonalen natürlichen Dürreerfahrung, um diese besser bewerten zu können. Karten dieser Anomalien über eine Sequenz von relativen Trockenjahren (1991 – 1995) zeigen eine gewisse überregionale „Dürrebewegung“ in Gebiete hinein, die generell als wenig oder überhaupt nicht dürregefährdet gelten.

Das Dürrerisiko, definiert als Unterschreitungswahrscheinlichkeiten partieller Maximalwertserien der Dürreindizes AMD und AMV, bestimmt (bis auf eine Ausnahme) mit einer Jährlichkeit T = 40 Jahre den Norden Costa Ricas als die Region mit dem höchsten Risiko schwerer Dürren.

Weiterhin wurde ein nicht-parametrischer statistischer Trendtest (Mann-Kendall) auf die Dürreparameter AMD, AMV und ND des Zeitfensters 1973-2003 angewendet, um die Frage zu klären ob Dürren im Testgebiet häufiger auftreten und von schwereren Ausmaßen gekennzeichnet sind. Für Costa Rica als ganzes konnte kein signifikanter positiver oder negativer Trend aufgezeigt werden, allerdings lassen sich in Bezug auf Dürrefrequenz und Schweregrad klare räumliche Muster ausweisen.

Ein weiteres Ziel dieser Arbeit ist es den Einfluss atmosphärischer Zirkulationsmuster auf regionale Dürren nachzuweisen, um kausale Zusammenhänge mittels Indizes besser beschreiben zu können. Eine nach statistischen Anforderungen, wie Linearität, vernachlässigbarer Autokorrelation und annähernder Normalverteilung durchgeführte Korrelationsanalyse zeigt großes Potential diese periodisch auftretende Abhängigkeit aufzuzeigen.

Signifikante (Signifikanzniveau $\alpha = 0{,}1$) Korrelationen (Pearson $r > 0{,}5$) konnten für Pazifische Meerestemperaturabweichungen (SST) und Dürreindizes (ACD, ACV) des Pazifischen Einzugsgebietes nachgewiesen werden. Der Atlantische Oszillationsindex (NAOI) korreliert mit Dürreindizes (ACD, ACV) des entsprechenden Atlantischen Einzugsgebietes. Damit wird der bedeutende Einfluss globaler Zirkulationsmuster auf hydrologische Dürre in Costa Rica deutlich.

Dürreentwicklung in der Region findet über unterschiedliche Skalenebenen, die zeitlich und räumlich verschiedenartig auf den hydrologischen Kreislauf einwirken, statt. Die natürliche Klimavariabilität wird maßgeblich durch ozeanisch-atmosphärische Zirkulationen beeinflusst, welche zusätzlich in Kombination mit physiografischen Einzugsgebietscharakteristika unterschiedlich stark zum tragen kommt (Persistenz). Eine Kreuzkorrelationsanalyse hat gezeigt, dass die Dürreentwicklung durch die Grundwasserneubildung während der Regenzeit zeitlich begrenzt ist. Die Klimavariabilität scheint also eher unmittelbar als längerfristig auf das hydrologische System einzuwirken.

Die Ergebnisse dieser Studie bestätigen die notwendige und mögliche Realisierung eines langfristigen Dürrevorhersagemodells, welches wichtige hydrologische Informationen zur saisonalen Dürreentwicklung liefern könnte. Dies würde zusätzlich Präventivmaßnahmen in einem Notfallplan erleichtern und zur nachhaltigen Wasserwirtschaft beitragen.

Acknowledgements

I would like to thank my lector Prof. Dr. S. Demuth for supporting this interesting work and Dr. Jens Lange for taking over the co-lecture.

During my stay in Costa Rica, data collection was greatly facilitated by ICE (Sadí Laporte & R. Chacón), CRRH (Patricia Ramirez) and UCR (Guillermo Brenes, Gilbert Vargas, Rafael Arce, Eric Alfaro, Dennis Salas, Guillermo Artavia, Francisco Solano, Luis Pablo Mora, Yálmar Sánchez & Alonso Brenes). I am very grateful to the Costa Rican professionals for providing helpful hydrological information in various discussions on the topic. Muchisimas gracias!

I really appreciated working with NIZOWKA, kindly provided by W. Jakubowski.

Thank you very much to my roommate and friend Marc for the back-up with accommodation, food and music.

I deeply owe my parents and grandparents special thanks for their lovely encouragement to my interests and plans.

After all, an invaluable part of the motivation to complete this thesis work came from Irene.

Christian Birkel

1 Introduction

CEPREDENAC (2005)

Central America and as a part of it Costa Rica, is characterised by a monsoon-type tropical climate. This results in a distinctive wet and dry season or in hydrological terms, low and high flow season. Seasonality in precipitation and flow regimes might experience periods of water deficits due to climate variability, which is commonly considered as drought.

Drought in the tropics is not a rare or random event, but a normal recurrent feature of climate. 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 emphasised not only the vulnerability of Costa Rican economies (agriculture), but also the threat for local population to shortages in water supply.

The unusually dry years of the 1997/98 El Niño event in Central America led to losses of 32,8 million dollars in Costa Rican agriculture alone (CEPAL, n.d.). Table 1.1 details Costa Rican droughts since the early 70's; notice that scarcely a decade goes by without at least one region of the country being affected by drought.

Major initiatives such as the AMIGO (FRIEND working group for Mesoamerica and the Caribbean), the CEPREDENAC (Coordination Centre for Natural Disaster Prevention in Central America) and the CRRH (Regional Commission for Water Resources) projects on hydrological extremes are evidence of the importance of an improved understanding of drought phenomena in the region. This study is carried out in the AMIGO project to contribute to such effort.

1.1 Assessment of the drought impact in Costa Rica

Water availability impacts a wide range of social, environmental and economic issues. It is essential for industrial, agricultural and domestic productivity, navigation, hydropower and recreation. Rivers must flow to provide sufficient freshwater habitats for a wide range of fauna and flora.
Drought impacts vary between regions and are as much a function of society and its land use as of the drought itself. The aim here is provide an overview of the most important impacts resulting from drought in the Costa Rican region.

a) Water Supply

The main priority in times of increased water depletion is to maintain a supply of drinking water of sufficient quality.
During the 1997/98 El Niño event the national water service AyA (National water supply company) found a surprising increase of 5 % in water consumption, which they attribute to increased temperature (AyA, 1998).
Generally, the water supply sector was due to forecasts quite well-prepared and immediately had some savings disposable. Miscalculations on the higher rate of consuming water caused the need to ration water in some parts of the country (mainly North Pacific region).

b) Agriculture

Agriculture is especially vulnerable to drought in countries of high agricultural production. All crops, whether irrigated or not, suffer a considerable reduction in yield during drought. Irrigated areas are often the worst hit, since a ban on irrigation is often one of the first restrictions on water usage imposed during times of drought.

- Arable crops

The delay of wet seasonal rains damaged the bean harvest, which is a main alimentation product and many farmers lost their harvest or obtained poor results including orange, palm heart, mango, melon, cassava, tequisque and ginger (CEPAL, n.d.). Some crops were more heavily damaged than others were, depending on their characteristics and their location. Economic consequences are more severe for small farmers, for example in the case of palm heart production. Citrus production is mainly in the hands of large industrial companies that are more likely able to survive lower production rates.

- Livestock

Surprisingly, one of the major impacts of the El Niño 1997/98 was on animal production, not even in the most drought-prone areas. Animals had been moved in preparation for the extended drought to according to experience non-affected areas (Northern Zone). Unfortunately, it had to be experienced that such a strong climatic phenomenon as drought does not respect any known frontiers or limits. Meat production was heavily affected and several thousand head of livestock died due to prolongation and spatial extension of this drought across normally unaffected regions. The typical ocean warming of the El Niño event lead to a significant decrease in fishery similar to well-known impacts on Peru.

- Forestry

Forests are particularly susceptible to fire during times of drought. An extended dry season leads to accumulation of combustible material in tropical dry forest areas (North Pacific region), which makes the control of fires extremely difficult.
The region reported two fires of large extension and the loss of several hectares of tropical dry forest and farm land.

c) Environment

Water quantity and quality deterioration affects not only drinking water supply, but also the natural ecosystems related to the water bodies. Low flow in a river does not provide adequate dilution of pollutants discharged into it, leading to risks for aquatic and, on occasion, even human life (Lloyd-Hughes, 2002).

In several Costa Rican rivers, it was to presume that the discharge level had fallen far below an ecologically minimum flow guaranteeing most species their aquatic ecosystem. Local population (personal conversations, 2005) subjectively reported increased fish mortality and crocodiles exhibited a more aggressive behaviour, because of reduced habitats. Due to the fact, that a definition of flow requirement yet not exists for Costa Rica, an exact assessment of impacts on the aquatic habitat is not possible.

d) Energy

Droughts can have serious implications for hydroelectricity production. Costa Rican electricity production is almost completely based on hydropower (~ 90 % according to CRRH, 2005). An extended dry period reduces national electricity production, leading to increased energy import and high prices. This are European experiences (European Environment Agency, 2001), which are assumed to be comparable to Costa Rica, but detailed information's on this sector are not published.

Table 1.1 gives an overview about damages and socioeconomic impacts in Costa Rica for the sectors mentioned above.

Tab. 1.1 Losses (in million dollars) 1997/98 in agriculture, livestock and fishery, after CEPAL (n.d.)

Sector and subsector	Damage			Increase of import	Decrease of export
	Total	Direct	Indirect		
TOTAL	**52.4**	**34.4**	**18.0**	**22.3**	**6.9**
Agriculture	**32.8**	**25.6**	**7.2**	**22.0**	**4.9**
For internal consumption	23.7	16.6	7.0	22.0	0.0
Rice	11.9	9.1	2.8	6.1	
Beans	11.1	7.2	3.9	13.1	
Corn	0.7	0.4	0.3	2.8	
For export	9.2	9.0	0.2	0	4.9
Sugar cane	3.0	3.0			2.0
Other	6.2	6.0	0.2		2.9
Livestock	**16.0**	**8.6**	**7.4**	**0.1**	**2.0**
Cattle	9.4	7.2	2.2		2.0
Aviculture	1.4	1.4			
Pasture	5.2		5.2	0.1	
Fishery Sector	**3.6**	**0.2**	**3.4**	**0.1**	**0.0**
Fishery	3.4		3.4		
Acuaculture	0.2	0.2		0.1	

1.2 Objectives and procedures

This chapter summarises principal objectives of this study, which can be condensed to three key tasks as follows below. Furthermore, the procedure points at achievements, as well as problems that rose during this work.

a) A methodology developed to describe drought patterns across Europe (Stahl, 2001) has to be translated to the tropical region of Costa Rica in order to obtain indices, which adequately determine regional streamflow drought. To assess such drought event definition the threshold level approach is modified to adapt to tropical flow regimes in order to properly describe their seasonality.

b) Drought indices, such as annual maximum and cumulated durations or deficit volumes are utilised to characterise temporal and spatial patterns of hydrological drought in Costa Rica by different applications:
    a. Overall maximum calculations are used to evaluate dry or wet years summarised among all stations.

b. Autocorrelation coefficients investigate sequences of dry and wet years regarding persistence in the hydrological system.
c. Anomaly Indices were utilised to detect actual drought severity levels and the interrelation of high and low flow season. Furthermore, maps to improve the understanding of regional drought development also spatially display this index.
d. The regional distribution of maximum drought indices was studied to reveal spatial patterns.
e. Variability Indices are assumed to point out the most affected regions by maximum events.
f. A frequency analysis of annual extreme values is used to base a definition of drought risk, which should help to gain knowledge about spatial drought patterns.
g. A trend analysis shall give clear answers for whether streamflow droughts have become more frequent and severe in Costa Rica.

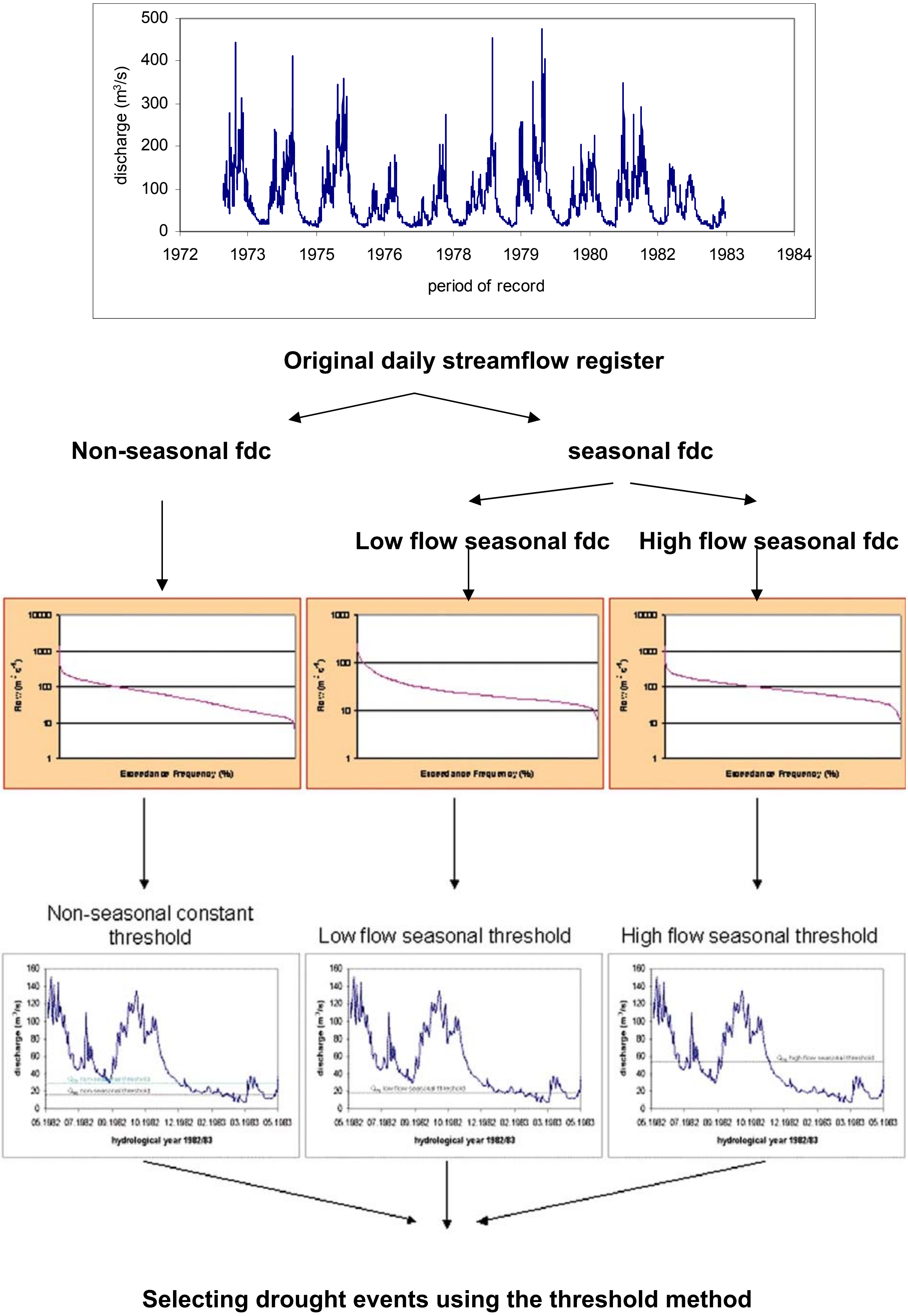
c) The linkage between atmospheric circulation patterns (ENSO, NAO) and regional streamflow drought indices is used to reveal relations of climate variability affecting hydrological drought. A statistical correlation analysis is the tool considered to satisfy this effort.

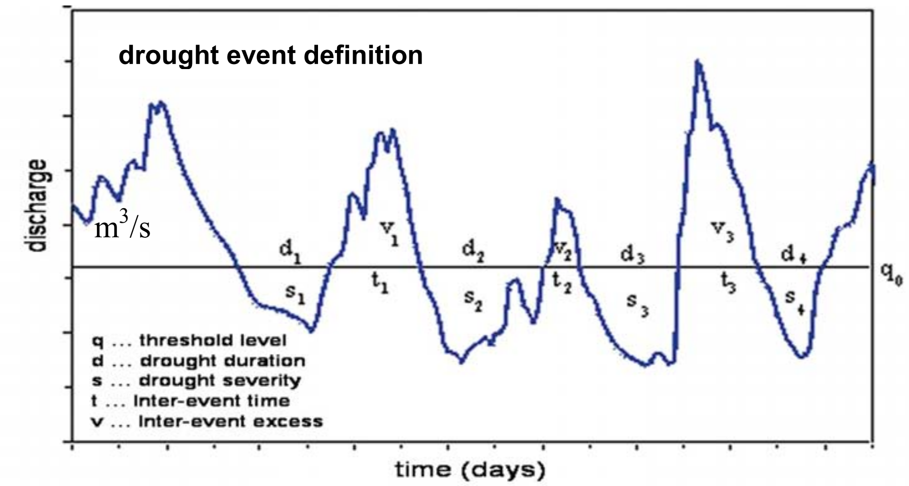
The compilation of a suitable data base for the regional drought study was the main task at the beginning of this work. Great help provided the Global Runoff Data Centre (GRDC), Germany offering daily discharge data, but the detailed analysis of available data revealed the necessity of a field trip to the research region in order to extend data series. In Costa Rica, it was possible to obtain, despite delicate data politics, complete daily discharge series with a common period from 1973 to 2003. Moreover, several institutions mentioned in Chapter 2.2 provided local expert knowledge and unpublished national literature on the topic could be found and is implemented in the study. A field trip during low flow season into the drought-proned regions such as e.g. the North Pacific region further improved the understanding of drought mechanisms in the Neotropics. Data processing and analysis were conducted in the office of the IHF, Germany.

1.3 Methodology

This chapter is supposed to procure in a brief, schematic outline called “drought study methodology” (Fig. 1.1) the principal methods to define drought events. The software NIZOWKA (Jakubowski et al., 2003) is introduced here, because it was further utilised to compute drought indices and frequency analysis basing the demonstration of temporal and spatial drought patterns.

Drought study methodology flow chart:





Drought Indices: Number Duration Deficit Volume

ND **AMD** **AMV** **ACD** **ACV**

Application:

Overall calculation
Persistence
Variability Indices
Drought risk

Anomaly Indices
Correlation with ENSO

Trend analysis

→ **Methods to study temporal and spatial drought behaviour.**

Fig. 1.1 Drought study methodology flow chart

NIZOWKA

Jakubowski et al. (2003) developed a computer program to select and analyse drought events based on the threshold level method. It also allows frequency analysis of determined drought indices like drought duration and deficit volume.

The program calculates the percentiles of the fdc to obtain the period of record threshold. The seasonal thresholds cannot be calculated by NIZOWKA and have to be obtained apart.

To further reduce minor and dependent droughts two restrictions can be imposed, the latter a pooling procedure is to be applied:

a) Minor droughts
   - a minimum drought duration (d_{min}) removes droughts with a duration of less than the specified number of days (in this study d_{min} = 5 days)
   - a minimum drought deficit volume (σ) removes droughts with a deficit less than a certain fraction α of the maximum drought deficit volume in the complete series of drought events (in this study σ = 0,005)

b) Dependent droughts

- According to Tallaksen et al. (1997) there are three different pooling procedures for dependent droughts; the moving average procedure (MA), the sequent peak algorithm (SPA) and the inter-event time and volume criterion (IC) implemented in NIZOWKA program. The IC will be explained here, for further information on other procedures see Tallaksen & van Lanen (2004).

A first event (d_i, v_i) is followed by a sequent (d_{i+1}, v_{i+1}) and pooled as follows:

$$d_{pool} = d_i + d_{i+1} + t_i \qquad \textbf{(1.0)}$$

$$v_{pool} = v_i + v_{i+1} - z_i \qquad \textbf{(1.1)}$$

t_i … inter-event time criterion (days)

z_i … inter-event excess volume ($1000 m^3$)

Different inter-event time criteria were tested (t_i = 3, 5 and 10 days). The IC of 10 days seems to overestimate drought events and is considered as little sensible for detecting droughts. In this study, the IC was chosen three days, however, both inter-event criteria three days, five days are valid, and no specific difference for the derived drought indices could be determined. Table 1.2 gives an example of the results provided by NIZOWKA.

Tab. 1.2 Result table example obtained from the program NIZOWKA

drought parameters							
profile: Caracucho			q_0 : 90,00 %				
river: Coto Brus			α : 0,005				
all year droughts 01.06. - 31.05.			d_{min} : 5 days				
			t_i : 3 days				
s	**mean s**	**min. Q**	**date of min.**	**mean Q**	**d**	**from**	**to**
$1000m^3$	$1000m^3$/days	m^3/s	**Q** (m^3/s)	m^3/s	days		
639,36	91,34	14,5	20.02.75	15,44	7	19.02.1975	25.02.1975
1978,56	131,9	13,5	31.03.75	15,07	14	18.03.1975	01.04.1975
5952,96	228,96	11,2	24.04.75	13,93	23	05.04.1975	30.04.1975
10972,8	255,18	10,4	05.04.76	13,61	41	08.03.1976	19.04.1976
12735,36	283,01	10,4	17.03.77	13,23	44	16.02.1977	01.04.1977
3006,72	214,77	11,1	15.04.77	14,38	11	09.04.1977	22.04.1977
648	92,57	14	05.03.78	15,47	6	02.03.1978	08.03.1978
1840,32	184,03	12,6	21.03.78	14,37	10	13.03.1978	22.03.1978
3067,2	180,42	12,1	20.03.79	14,41	17	09.03.1979	25.03.1979

The table gives a description of the site (river, station etc.) and the program features (threshold level, IC etc.). In the first column, the deficit volume (s) in $1000m^3$, defined as the sum of the daily deficit flow below the threshold level is displayed. The next column gives the deficit volume averaged by the drought duration (d) in days, followed by the minimum runoff and its occurrence date, as well as the average runoff of the drought event.

Drought duration is defined as full drought duration minus pooled periods by the inter-event time criterion above the threshold. The authors of NIZOWKA define this pre-processed duration as the “real drought duration”. The last two rows display the drought period “from” the beginning “to” its last day. The complete program results are the basis for all further drought analysis like the derivation of drought indices, which either have to be selected for the annual maximum parameters or standardised by mean flow for the deficit volume indices.

Finally, statistical methods are briefly introduced in the forthcoming chapters to not interrupt comprehensibility of the continuous text.

2 Study area

2.1 Introduction

Central America is composed as a geographical, physiographical, geological and meteorological heterogeneous land bridge between North and South America, called Isthmus.

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 (Fig. 2.1). 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 51110 square kilometres.
With two coastlines, one in the east (Caribbean Sea) and the other in the west (Pacific Ocean) marking its natural borders, the region is also known as the "Neotropics".

Costa Rica was chosen for this study, from all Central American countries participating in the AMIGO working group for Mesoamerica and the Caribbean, due to a more representative daily discharge dataset (Chapter 2.2), which covers most of the countries different climatic regions.

Fig. 2.1 Costa Rica and its political borders, after MapMart (2004)

2.2 Data base

2.2.1 Hydrological data for drought analysis

National as international hydrological studies depend on available datasets of adequate resolution and quality. International data centres like the Global Runoff Data Centre (GRDC) were established to freely provide global hydrological data to research projects like FRIEND (Flow Regimes from International Experimental and Network Data, CEH, 2001), AMIGO (FRIEND working group for Mesoamerica and the Caribbean) and users.

According to GRDC, Germany a total of 49 Costa Rican gauging stations on a daily based streamflow record is available. This data was published for the time window 1973-1993, but at a closer look too many large gaps of several years appeared. When this study was carried out in the AMIGO project, the Instituto Costarricense de Electricidad (ICE) database provided a considerably update to the GRDC database.

ICE, as a national operating institution, provides all possible hydrological data and put 18 gauging stations of the GRDC record with the common period 1973-2003 and of partly corrected data series at our disposal. These 18 representative stations were selected to guarantee most natural streamflow data as possible. Developed catchments by hydro-electric power generation were disregarded, because of regulation effects on flow patterns. More difficult to distinguish are catchments with irrigation schemes or land use change due to the lack of information about location, volume and timing of artificial influences.

Irrigation schemes and groundwater extraction were legitimated in a law of water dating from 1949 and since then demand increased for over 75 % and common practice is now to supply the need for water from innumerable diffuse sources. According to the national chamber of legislation (2005), a new law for water is almost developed and about to enact. In fact, it can be recommended to count with several diffuse artificial components, especially in agriculturally used regions (Caribbean, the North Pacific region and the Northern Zone). Nevertheless, artificial influences on selected flow records may not exceed the natural contribution.

Plotting daily hydrographs for all stations was used to subjectively discover discontinuities, jumps or outliers in the mean daily streamflow record. More information about errors at the gauging stages could not be examined, because raw data was not made accessible. Therefore, some records showed gaps of missing data (Fig. 2.2), which had to be properly closed by adequate methods in order to increase ability for expressive statistics and computation.

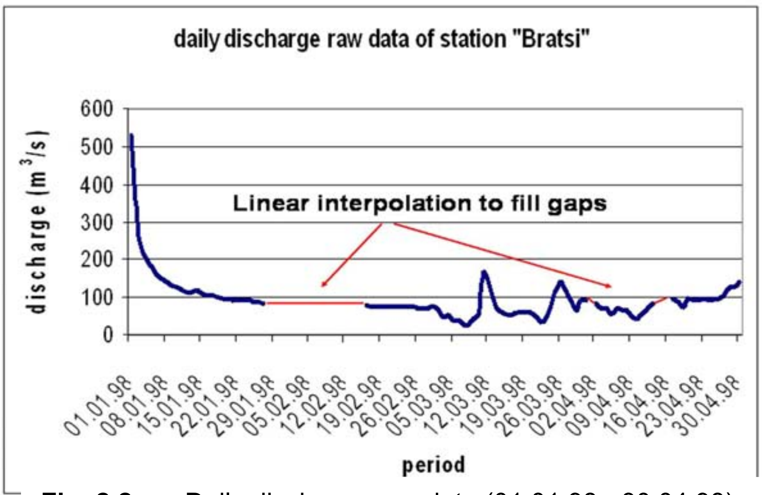


Fig. 2.2 Daily discharge raw data (01.01.98 - 30.04.98) of station “Bratsi”

Gaps of less than one month were simply corrected by linear interpolation and by correlation if a neighbour station in the same catchment was available (Fig. 2.2), ensuring same climatologically and physiographic characteristics to guarantee similarity of runoff generation mechanisms.

In the case of several missing months of a year, this particular year has to be neglected and the gap closed making computation of drought indices sure.
Figure 2.3 gives a general overview about principal catchment's delineation, rivers, climate stations and streamflow gauges used in this study.

Eighteen stations covering all major climatic regions of Costa Rica with a common period from 1973 to 2003 of daily data series without missing values. Eleven stations contain the full record length of thirty years. The other seven stations count with the common period and lengths of more than 23 years. This was considered the best compromise between a long common time window and good spatial coverage.

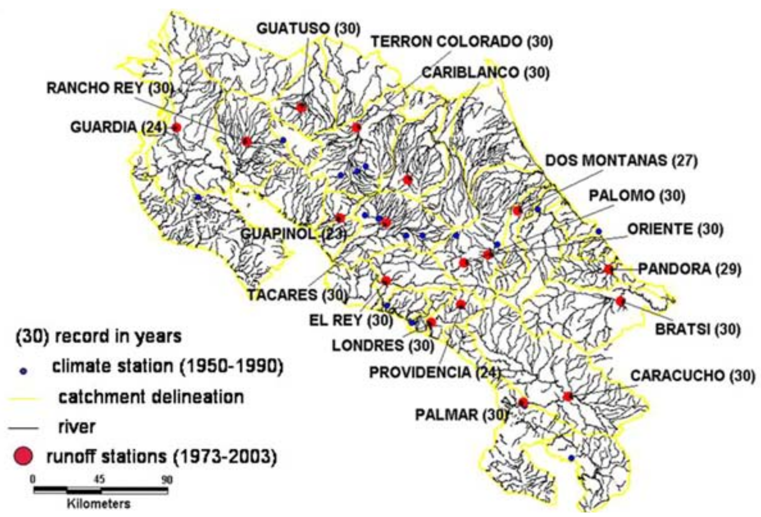


Fig. 2.3 Climate stations (blue) and streamflow gauges (red) ordered by principal catchment's delineation

The following table (Tab. 2.1) shows the register of all available gauging stations on a daily streamflow basis displayed above in Figure 2.3.

Tab. 2.1 Gauging stations on a daily streamflow record for the period 1973-2003 (ICE, 2005)

river	station	area (km^2)	altitude (m)	period	status
FRIO	GUATUSO	254	44	1973-2003	corrected
SAN CARLOS	TERRÓN COLORADO	2040	54	1973-2003	full length
SARAPIQUI	CARIBLANCO	73	752	1973-2003	full length
TEMPISQUE	GUARDIA	955	13	1979-2003	full length
TENORIO	RANCHO REY	288	20	1973-2003	corrected
BARRANCA	GUAPINOL	203	240	1977-2000	full length
POAS	TACARES	202	598	1973-2003	full length
GRANDE DE CANDELARIA	EL REY	661	94	1973-2003	full length
NARANJO	LONDRES	210	170	1973-2003	full length
SAVEGRE	PROVIDENCIA	128	1440	1979-2003	full length
GRANDE DE TERRABA	PALMAR	4767	13	1973-2003	corrected
COTO BRUS	CARACUCHO	1131	98	1973-2003	corrected
REVENTAZON	PALOMO	371	1077	1973-2003	full length
PEJIBAYE	ORIENTE	227	619	1973-2003	corrected
PACUARE	DOS MONTANAS	652	69	1973-2000	corrected
ESTRELLA	PANDORA	635	15	1973-2003	full length
TELIRE	BRATSI	2121	35	1973-1998	corrected

The record of streamflow data originates from catchments of variable size including 73 km^2 to 4767 km^2. According to Tallaksen & van Lanen (2004), catchment's size does affect low flow analysis, when different climates cause a superposition of different hydrological regimes. This can be excluded in the case of the study area; because selected catchments do not cross different regional climatic zones as the further physiographic introduction of the study area (Chapter 2.3) proves. The 17 gauging stations cover 16 out of 35 principal catchments and all regional climate zones.

2.2.2 Meteorological data

Further precipitation analysis includes 17 climate stations (shown in Fig. 2.3 as blue dots) with a register of more than 30 years of monthly data. Unfortunately, the Northern Zone, as well as the mountainous Southern Region, is poorly represented. Due to a compromise of large record and best coverage, earlier mentioned stations are selected for the period from 1950 to 1990. The NUMEROSA database was made accesible by CIGEFI (Centro de Investigaciones Geofísicas), UCR (Universidad de Costa Rica) and CRRH (Comité Regional de Recursos Hídricos). Figure 2.4 shows mean monthly precipitations of different, colour-coded climate stations for the period from 1950 to 1990.

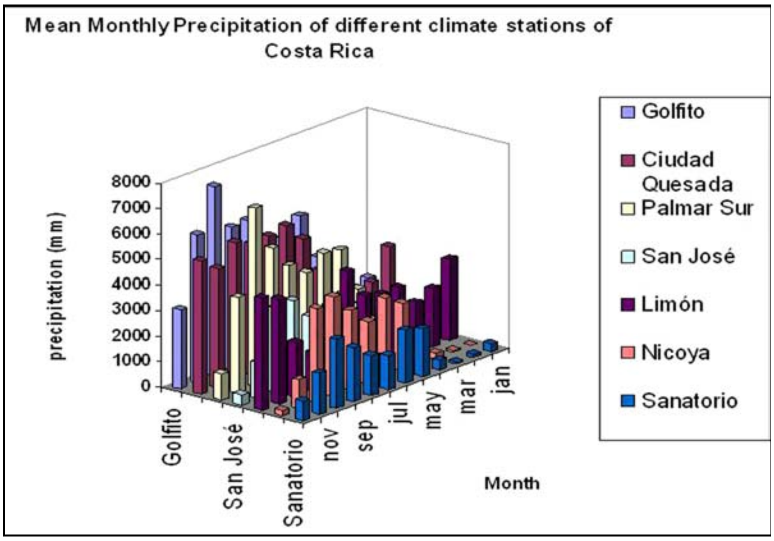


Fig. 2.4 Mean monthly precipitation distribution among different climate stations of Costa Rica for the period 1950-1990

No prerequisite analysis to evaluate consistency could take place, because data was already delivered as derived monthly averages, but according to personal information's (Brenes, personal conversation, 2005), this data provided great help in various international studies.

The meteorological data base is supposed to support further interpretations by comparing climatic characteristics for different results of the drought analysis. Chapter 4 about linking atmospheric circulation patterns to regional streamflow drought includes meteorological indices freely available from NOAA, USA. Numerically derived indices determining teleconnection patterns could be prolonged by paleoclimatological studies to large scale time series (18th century until present).

In this study, are applied the North Atlantic Oscillation Index (NAOI) and the El Niño-Southern Oscillation (ENSO) Indices, such as the Southern Oscillation Index (SOI surface pressure departures) and the Sea Surface Temperature departures (SST).
A plotted example of the Southern Oscillation Index (SOI) is given below (Fig. 2.5).

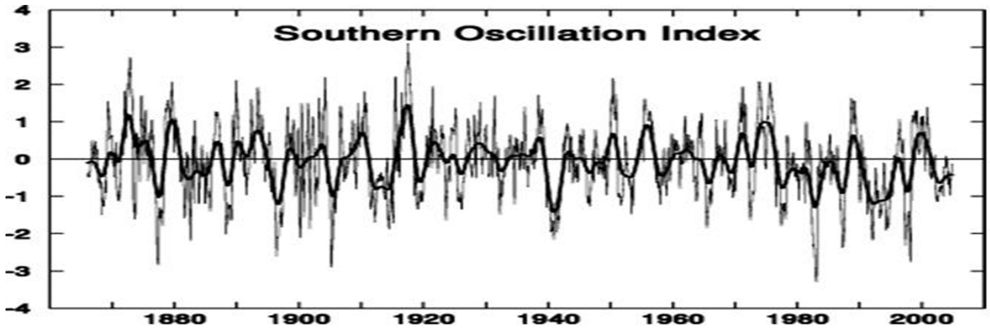


Fig. 2.5 Plotted Southern Oscillation Index, after NOAA (2004)

2.2.3 Thematic data

All thematic data used in this study were made accessible by Comité Regional de Recursos Hídricos (CRRH) from their Central American data base. The Geographical Information System for Costa Rica build up 2004 from 15 topographic map units (1: 50000) contains hydrogeographical information like catchment's delineation, digital elevation model, drainage system, lakes and estuaries.

The latest national scale GIS published, based on NASA's 2003 Central America mission aerial photos transferred into scale 1: 25000, was converted into the National GIS Atlas of Costa Rica (Escuela de Ingeniería forestal del Instituto Tecnolólogico de Costa Rica, 2005) including important information on geology.

Figure 2.6 shows the principal water division of the Pacific and Atlantic Vertient and Costa Rican water bodies separated into rivers (organised by main catchments), lakes, lagoons and reservoirs. Lagoons are defined as shallow, coastal bodies of water separated from the ocean by barrier islands. A cross section through this, due to a large coastline important hydrological unit includes mangroves and often an estuary.

For Costa Rica, shallow, inland water bodies influenced by seasonality of rivers and old, inactive volcano crater seas exclusively influenced by precipitation, instead of tidal changes are also defined as lagoons. Both types exhibit the same hydrological influence in form of precipitation and evaporation, which results in fluctuating water temperature, salinity and stage.

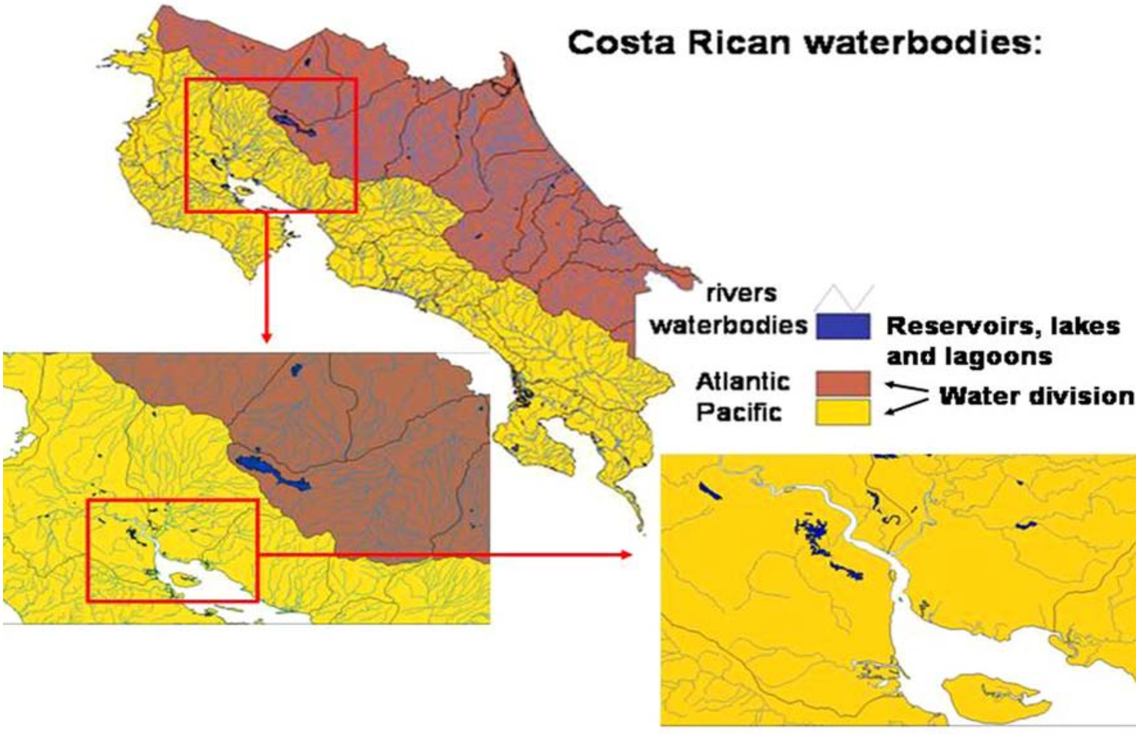


Fig. 2.6 Major water division (Atlantic/Pacific) and water bodies of Costa Rica (reservoirs, lakes and lagoons)

The total area of all artificial reservoirs is 83,4 km^2, of all lakes 3,3 km^2 and of all registered lagoons 146,4 km^2. Surprisingly low seems the small amount of natural lakes compared to the total area of 51.110 km^2, which might be an indicator for high, hydrogeological permeability and an important characteristic for low flow.

Table 2.2 (under Appendix) gives the main characteristics of principal watersheds visible in Figure 2.6, above. These follow an order from one to thirty-five and are listed according to area (km^2), drainage density (km/km^2), mean elevation (m), mean slope (%) and Relief Ratio (m). Areas vary from 200 km^2 to 4781 km^2 and generally reflect a high drainage density (mean: 4,2 km/km^2). This value must be considered as strongly dependent on scale. A channel system order after e.g. Horton or Shrive does not exist yet according to present knowledge.

The dentritic and in some smaller scaled occasions radial drainage system (Silva, 1991) was digitised from 1: 50000 topographical maps and can be compared to a very good drainage capacity according to the literature (Dyck & Peschke, 1995). This generally and particularly for Costa Rica, points to seasonal climates with high precipitation intensities, high base flow indices and superficial runoff due to high relief ratios. If these mentioned factors coincide with low flow behaviour, has to be investigated yet. Mean slope characteristics reflect high relief ratios and vary from 0,1 % to 17,3 %.

2.3 Physiography

2.3.1 Physical geography and geology

Physical geography

According to Silva (1991), Costa Rica can be divided in four major physiographical regions (see Fig. 2.7):

1- The *“Cordillera”*, which represents a mountain range cutting the country lengthwise in two parts: the Pacific and the Caribbean.

It consists of different sections, which vary from geology, materials and morphology. Most of these sections are of volcanic origin, while the southeast of the “Cordillera” is formed of high territories with plagial structures and rifts still under the process of heavy elevation.

The volcanic “Sierras” of Costa Rica are active volcanoes and form part of the “Pacific Ring of Fire”. They seem to be characterised as vertebral of the “Cordillera” mountain range organising the rest of the territories, such as the major water division into a Pacific and a Caribbean contribution area.

2- The “*Central Valley”* is an intermountainous depression of topological plain character enclosed in the north by several volcanoes (e.g. Poas, Barva…) and by various sections of the “longitudinal” mountain range in the south, east and west.

Such delineation extends about 50 km from east to west and about 20 km from north to south, with a mean elevation of 1100 m above sea level. Although, its base is of tertiary marine sediments, geologists define its origin as tecto-volcanic, result of the elevation process of the “Cordillera”.

Ninety percent of the population concentrates in the Central Valley living in the capital San José and other important cities.

3- The “*Meridian Valley”,* located in the south near to the border to Panama, is an intermountainous valley formed between two sections of the Cordillera.

Its mean elevation is about 800 m above sea level and it extends 110 km from north to south with a width of about 20 km. Two major watersheds of opposite character, confluence to river “Grande de Terraba”, which breaks through the small “Fila Brunqueña” to drain into the Pacific Ocean.

4- The *Peripheral Plains* are uniformed by their elevation, but vary distinctively in their origin, climate (Chapter 2.3.1) and composition of materials.

In general, the mountain range decreases to areas of fewer slopes on both sides to the east and west.

The *Caribbean plain* is a synclinal watershed dated back to the Eocene and dominated by extensive lava deposits at the mountain foot. Layers of fluvial sediments from the Quaternary overlay these volcanic materials interrupted by more in the interior situated small volcanic buildings. It is believed, that this small volcanoes formed an archipelago to anchor the transported sediments, so the actual inundation plain was formed by holding back river materials.

The *Pacific Plain* between the mountain ridge and the Pacific Ocean is much more narrow (20 – 30 km) than its counterpart on the other side of the mountain range. Steep slopes form watersheds of high mean elevation and mean slope with its typical hydrological characteristics of high sediment transport capacity, high peak flows and short concentration time etc. An exception has to be made in the northern region of “Guanacaste”. There the drainage basin of the river “Tempisque” is defined as a plateau. All kind of materials can be found. Sometimes the narrow band between ocean and mountains simply consists of an alluvial fan from the draining river.

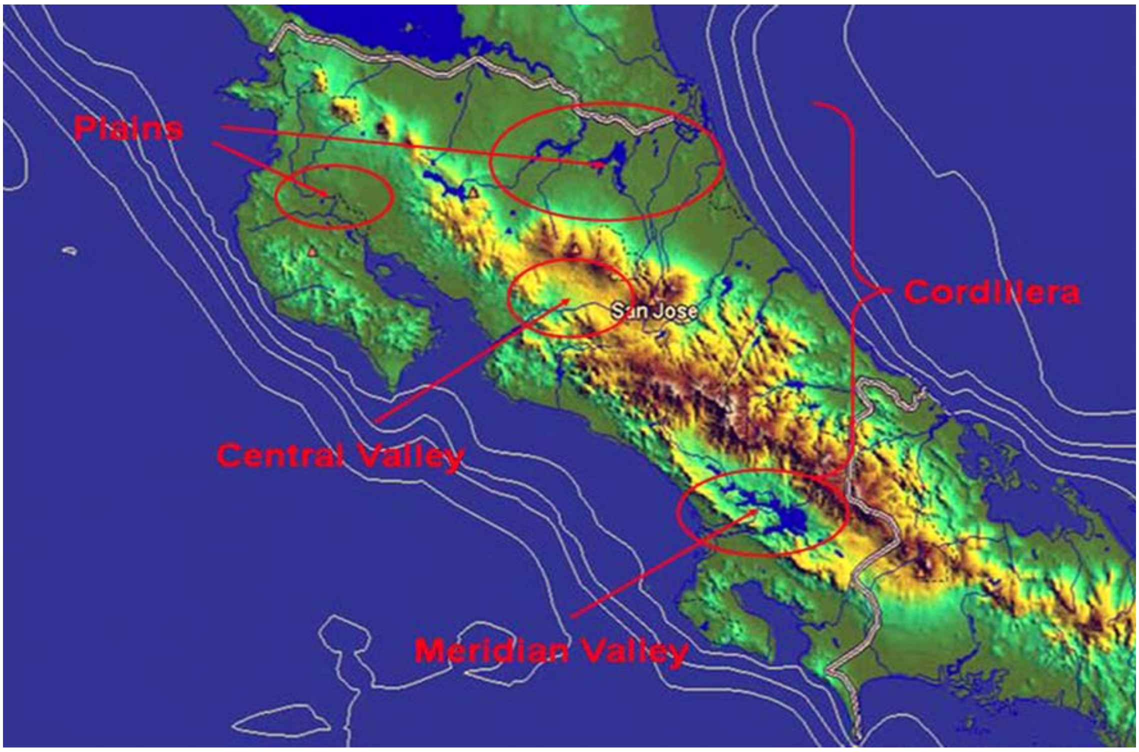


Fig. 2.7 Topography of Costa Rica modified after MapMart 2004

Hydrogeology

Hydrogeology is absolutely connected to geology transferring potential aquifer properties to geological formations. These formations are of different origin and of varying hydrogeological capacities and may play a very important role as reservoirs in catchments widely affecting low flow behaviour of rivers.

As discussed in the section about “Physical geography”, the main geographical division can be taken as reference for different geologic formations. First of all, the “Cordillera” has its origin in volcanic manifestations mainly occurring during Quaternary. Materials basically consist of lavas and pyroclastics like Ignimbrite, which are of andesitic and basaltic composition. Other geologic formations found in the plains that are older volcanic materials, dating from Tertiary and are as important for hydrogeology as recent fluvial and marine sediments.

According to Losilla et al. (1992), the surface is of great importance to groundwater recharge and to regulation of superficial waterflow. Specially, in the “Cordilleras” deep volcanic soils favour characterised by high infiltration capacities coupled with high hydraulic permeability of the fractured lava formations and high annual precipitation rates, aquifers of very high capacity. The aquifer systems of the plains mainly consist of fluvial and marine sediments and play an important role for local water supply. Depending on the relief gradient, some aquifers of the plains are fed by connected volcanic aquifers of higher altitudes (Losilla et al., 2001). The recharge area of great parts of the aquifers of the plains cannot be defined properly. Nevertheless, aquifers preserving capacity originated in other contributory subterranean units might be of great importance during low flow periods.

The following Table 2.3 gives a brief overview of the main exploited aquifer systems in urban areas. Note that “percolation” under “recharge” is a hint for other contributing recharge areas and the volcanic aquifers of very high capacity (transmissivity).

Tab. 2.3 Hydrogeological important formations modified after Losilla et al. (2001)

aquifer	location	origin	depth (m)	extension (km^2)	type	recharge (l/s)	transmissivity (m^2/d)
Colima superior	Central Valley	Quaternary	100	170	unconfined	2800	500-9500
Colima inferior	Central Valley	Quaternary	100	230	confined/ unconfined	percolation	500-7500
Barva	Central Valley	Quaternary	30-60	135	confined/ unconfined	3800	400-530
Bagaces	North Pacific	Tertiary/ Quaternary	11-45	1300	unconfined	percolation	745-2800
Liberia	North Pacific	Quaternary	25-100	430	unconfined	percolation	7-14

Due to overexploitation and excessive use of agrochemicals, great parts of Caribbean coastal aquifers and the Central Pacific coast are exposed to salinity and pollution.

2.3.2 Climate

Circulation

High temperatures and precipitation throughout the year generally characterise Costa Rica, as a tropical country. Due to a relative small continental landmass, there are little annual climatic variations. In fact, regional climate is dominated by regional circulation patterns like

a) the shifting Inner Tropical Convergence Zone (ITCZ),
b) the trade winds from the east and
c) the polar depression.

Other climatic phenomena like hurricanes also cause a change in weather, but the three circulation patterns mentioned above are the most important. Global circulation patterns like the El Niño Southern Oscillation (ENSO) have their effects on Central American climate, which occasionally overlaps regional effects (Coen, 1951 and Hastenrath, 1976).
Wind (Fig. 2.8) represents the most important annual climatic variation and fundamentally affects variable local climates. Differing wind systems from the Pacific Ocean and the Caribbean Sea, plus the characteristic topography within its mountain range from the north to the south can be found in typical precipitation patterns.

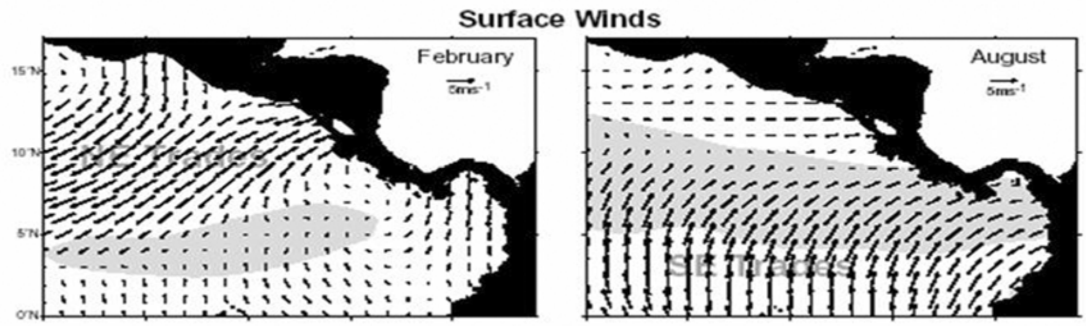


Fig. 2.8 Mean monthly fields of surface wind velocity at the Pacific Ocean for February and August (Fiedler, 2002)

Surface winds in the region of Costa Rica seasonally change when the Inner Tropical Convergence Zone (ITCZ) moves between the trade wind belts north and south with a delay of approximately two month after the sun's zenith (Coen, 1951). The annual cycles of winds presented in Figure 2.8 suggest that the observed cycle of rainfall patterns exhibit seasonal variability that appears to be related to the large-scale wind field, in particular, the convergence of the trade winds in the ITCZ. During December and January (left panel in Fig. 2.8), as the ITCZ moves south and strong trade winds blow, they impulse labile air masses over the Caribbean Sea to arrive at 10° northern longitude.

By hitting the coast, winds loose power and due to topography, force transported humidity to climb up, condense and to precipitate (Enfield & Alvaro, 1999). The migration of the ITCZ is at its annual “Southernmost Extreme” in February, but coastal winds blow throughout the year bringing intensive rainfalls to the Caribbean all year round. From May to June (right panel in Fig. 2.8), the ITCZ moves north dominated by southeast trade winds bringing extensive rainfalls to the Pacific Coast, until in August its “Northernmost Extreme” is reached.

The relative strengths of the northeast and southeast trade winds vary considerably during the year, influenced by e.g. winter high pressure systems over the Gulf of Mexico and the Caribbean Sea, while the polar depression forces strong winds through low altitude passes of southern Mexico and Central America (Fiedler, 2002). This effect of strong winds at “low altitude passes” can be seen in the left panel (February) of Figure 2.8, bringing higher precipitation rates to the Northern Zone during dry season.

Spatial precipitation patterns

Mean monthly precipitation series from stations all over the country were collected to derive a mean annual precipitation map of Costa Rica. The period 1950-1990 was found to fit best a large record and as many stations as possible to study a general spatial rainfall behaviour.

17 stations were selected and an interpolation with a grid cell size of 500 m x 500 m computed. This information was coupled with a detailed annual precipitation map from the National Meteorological Institute (IMN) to create a contour map of annual rainfall distribution (Fig. 2.9). Reported (ICE, IMN) strong elevation effects are subjectively taken into account by this calculation. Hastenrath (1976) found out that in tropical Costa Rica precipitation amount increases just up to a specific elevation range and is then about to decrease by exceeding a certain limit. The elevation range of the maximum rainfall limit was discovered to be close to 1000 m altitude.

In fact, the results of Hastenrath (1976) can not be confirmed in Figure 2.9.

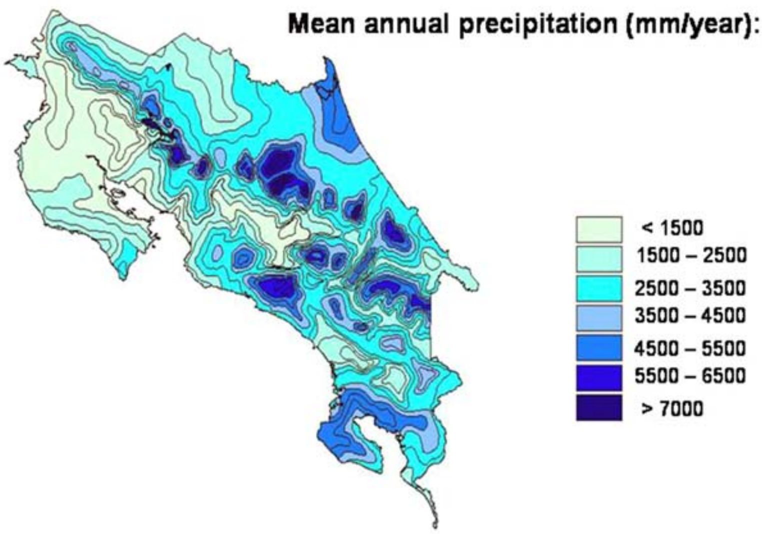


Fig. 2.9 Interpolated mean annual precipitation map modified after IMN

There are small regions, where the mentioned decrease in precipitation can be found after exceeding a certain limit of altitude like e.g. at some parts of the Central Pacific region. Generally, however, the average annual precipitation amount clearly increases coinciding with topographical altitudinal patterns.

Figure 2.9 shows relatively high annual precipitation rates at the Caribbean Coast, the Northern Zone and the South Pacific coast. This can be partly explained by the shifting ITCZ and its trade wind system.
However, both oceans catching large rainfalls nearly all year round influencing the Northern Zone of Costa Rica characterised by a plain topography. Furthermore, the Pacific Coast can be divided into the drier north and the more humid Central Pacific coast with a very distinct dry and wet season. The Central Valley can be seen as a climatologically special case influenced by the Caribbean Vertient. The higher altitudes of the Central Valley receive typical high precipitations of the Caribbean Vertient contributing to the Pacific water division.

Fig. 2.10 Generalised climatic regions of Costa Rica according to IMN (2000)

According to IMN (2000), six different climatic zones can be described as shown in the following figure (Fig. 2.10), which coincide with spatial precipitation patterns (Fig. 2.9 above), major physiographical land units (Fig. 2.7) and flow regimes (see further Fig. 2.15).

Temporal precipitation patterns

A mean monthly rainfall regime study is carried out by the same climatological data set mentioned above in order to investigate seasonal precipitation patterns. This climatological chapter is supposed to base the interpretation of further streamflow drought analysis. Seven selected representative climate stations for the regional climatic distinction are chosen to describe seasonal rainfall patterns for the common period 1950-1990. Figure 2.11 shows a generalised regional distribution of characteristic climatic regimes.

In general, a difference in magnitude as well as seasonal variation of rainfalls between the Pacific and Caribbean Vertient can be seen. The selected Caribbean station (violet) shows precipitation all year round with an only weak distinction of dry and wet season.
The Northern Zone station shows a high magnitude of monthly rain, but in this case, a perceptible dry season during January, February and March can be noticed. The most seasonal distinction show the Pacific stations of the North, the Central Pacific and the Central Valley (blue) with almost no precipitation in January.
Under normal conditions, the dry season takes place from December to March and rainy season from May to October. April and November can be seen as transition from one epoch to the other.

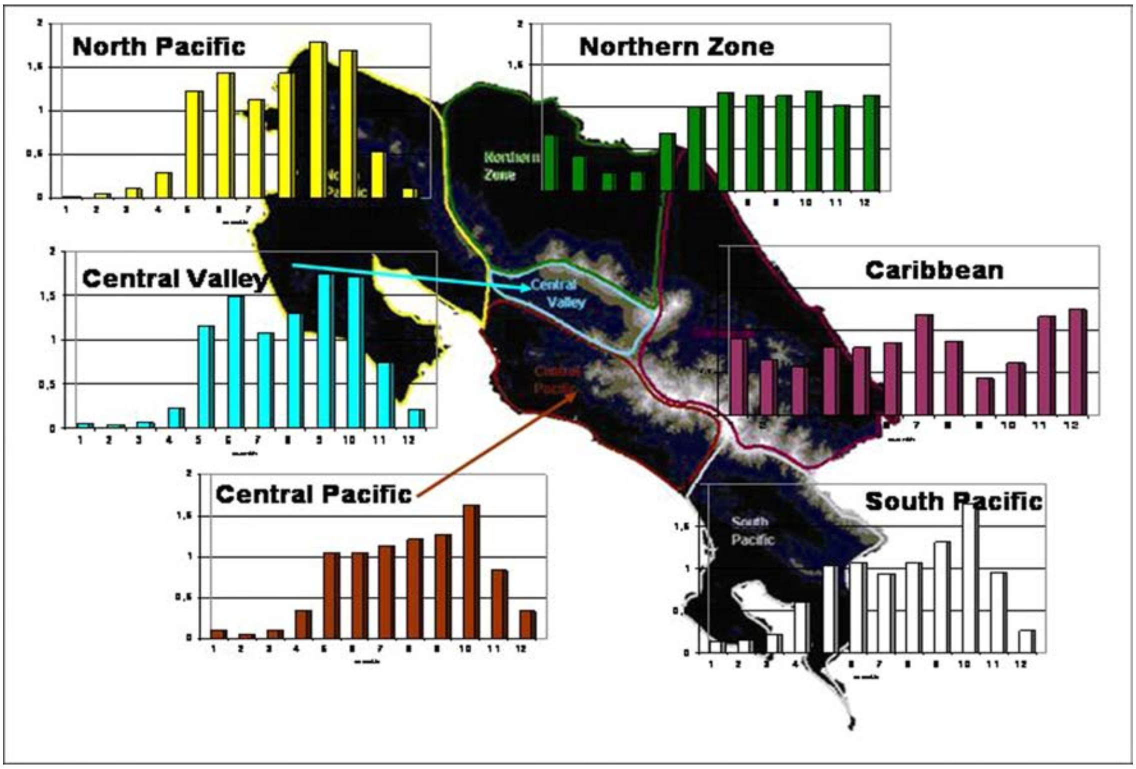


Fig. 2.11 Selected representative mean monthly precipitation regimes (1950-1990) for the main climatic regions

Several precipitation registers like the Central Valley and the North Pacific region show a phenomenon called “Veranillo” or “little summer” in July. This is characterised by a significant decrease in rainfall magnitude with a prolongation of the phenomenon up to three weeks. In these regions rainfall magnitude decreases due to a change in the circulation system. This is caused by an intensification of north winds in the Upper Troposphere (Hastenrath, 1966). The typical monthly rainfall regime of the Central Pacific does not show a decrease in magnitude of precipitation (“Veranillo”) and rainy season experiences a prolongation until December. A general higher monthly magnitude of rainfall can be seen at the Southern Pacific station (white colour) with the same seasonality.

Furthermore, innerannual (monthly) precipitation variability regimes (Fig. 2.12) were derived according to the procedure presented below, in order to generate a view on seasonal variability of tropical rainfall in Costa Rica:

$$\textbf{Variability (\%)} = \left(\frac{S}{M_p}\right) \times 100 \qquad \textbf{(2.0)}$$

S ...Standard Deviation of monthly precipitations (-)
M_p ...Mean monthly precipitation (-)

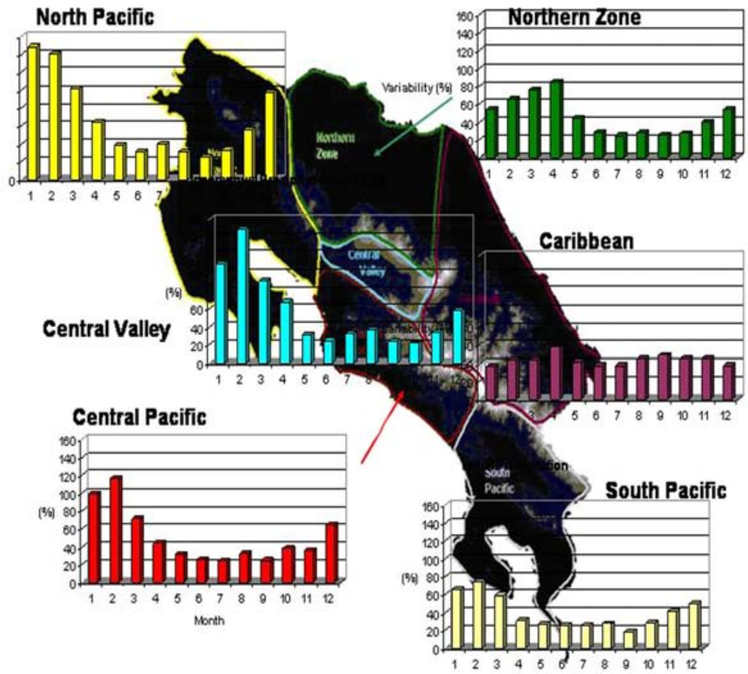


Fig. 2.12 Selected representative monthly precipitation variability regimes (1950-1990) according to climatic division

Most seasonal variability in Figure 2.12 can be noticed during summer (December – April). Stations on the Pacific Vertient show very high variability's for summer season, up to 160 %. It is to expect that the more rainfall variability during dry season, the more exposure to drought conditions.

2.3.4 Hydrology

Summary statistics

A closer look has to be taken at the discharge data in order to define summary statistics, which acknowledge a generalised, brief perception of Costa Rica's major hydrological units. The summary statistics are utilised to predefine major hydrological characteristics for further drought analysis.

Figure 2.13 displays the summary statistics table (Tab. 2.4) to better visualise basic hydrological characteristics. These are presented as log-normalised bar charts for each station guaranteeing comparability due to identical colour codes (see legend of Fig. 2.13) and scale. The thematic background shows the principal topographic catchments of Costa Rica.

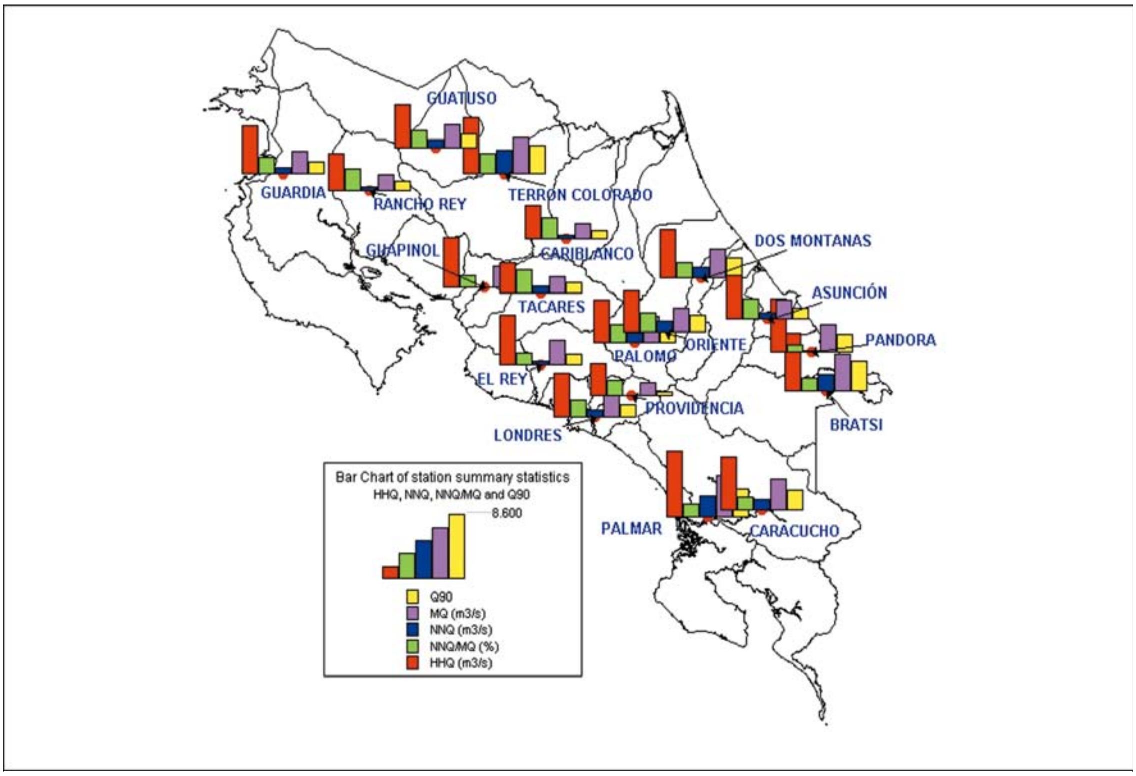


Fig. 2.13 Summary statistics (1973-2003) of river gauging stations with log-normalised bar charts

The base flow index (BFI), which is not presented visually above (Fig. 2.13) gives the ratio of base flow to total flow, calculated from a separation procedure using daily discharges. It is considered a measure of river runoff from stored sources and a general catchment descriptor. Further application can be found in Tallaksen & van Lanen (2004).

The BFI was introduced to the summary statistics in order to compare catchment's reservoir properties. In general, little variability among the BFI's with a relative high average value of 0,68 for investigated river flows can be seen. This chiefly points to good storage capacities across Costa Rica. The lowest value, derived for station "Pandora" (BFI = 0,44) at the Caribbean is an agriculturally used catchment without any natural vegetation and it is of impermeable geological structure providing little reservoir capacity.

The mean yields (Mq) vary from 10 l/s*km^2 to 154 l/s*km^2 among catchment's. Interesting here is that the lowest values seem to be connected to the traditionally as dry areas proclaimed catchments, such as the North Pacific and one station at the Central Pacific. This would lead to speak of high storage capacities, which are not always reflected by high base flow index values. However, Losilla et al. (2001) confirm good aquifer characteristics in these regions.

Figure 2.14 shows the catchment's BFIs regionalised at a national scale with Mq's (l/s*km^2) as varying sized red dots at the gauging station's location. Colour blue reflects low BFI values and red, high BFIs according to the figure's legend.

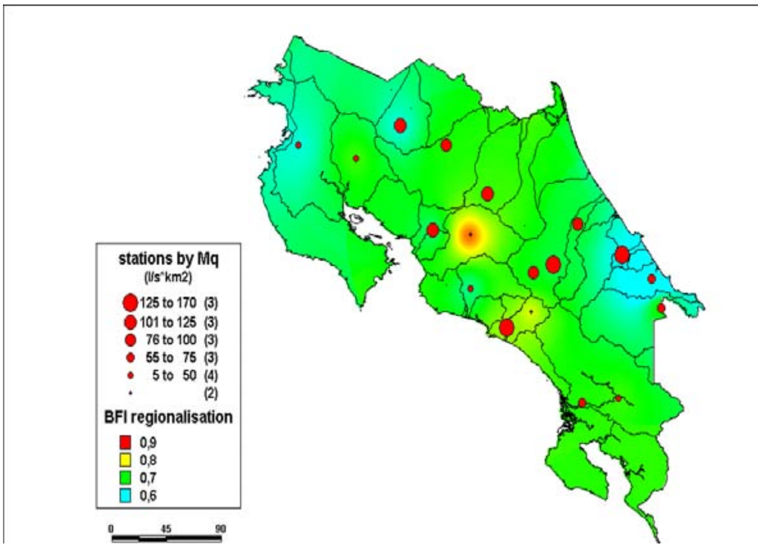


Fig. 2.14 BFI regionalisation across all catchments at a national scale and period of record (1973-2003) with the station's Mqs as varying size dots (red)

The most extreme BFI of 0,86 shows station "Tacares" located at the Central Valley, which catchment is known for high permeability and excellent reservoir capacities according to the high level of groundwater consumption.

A short discourse about the interpolation method used for regionalisation of drought parameters has to be given. Generalised hydrological maps present an effective tool to demonstrate spatial drought characteristics. The method of interpolation is Inverse Distance Weighting (IDW), which implements a distance weighted average of data points to calculate grid cell values. This weight can be manually chosen depending on the number and distance of data points. According to Gottschalk & Krasovskaia (1998) and Sauquet et al. (2000), the IDW method was considered to accomplish well the approach to regionalise drought. In the case of this study, the IDW interpolation method is exclusively utilised to visualise and interpret spatial drought patterns due to high uncertainties among the estimators. Estimated drought parameters at ungauged sites must not be used for calculations, because estimation errors highly exceed confidence limits.

The highest low flow variability coefficient (NNQ/MQ = 27 %) of station Tacares respectively confirms the assumptions of excellent reservoir capacities due to the lowest extreme water deficit of all stations (Tab. 2.4 – orange column).

The stations of the Caribbean Vertient show little variation of mean flows, which points to interpret towards less human activity and less climate variability. Based on present knowledge, Central and South Pacific stations are expected to be of low human activity and provide aquifer characteristics of high capacity to maintain constant streamflow stages. A contrary picture tell the more variable mean flows of North Pacific stations. In the case of "Rancho Rey" the loss of natural vegetation coverage and high variability of rainfalls provoke high variability among expected monthly flow.

However, an interpretation of the hydrological situation for these station registers on the hand of single statistical characteristics (e.g. MQ) can not be considered adequate. Their location in relatively similar regional climates indicates strong interference by reservoir characteristics. Summary statistics are limited to point out tendencies and to present a general overview of hydrology.

Table 2.4 below shows: the absolute maximum (HHQ) and minimum (NNQ) discharges, mean flow (MQ), mean yield (Mq) of the whole streamflow register and a low flow variability coefficient (NNQ/MQ) computed for the extreme value NNQ standardised by mean flow. This coefficient is considered as a first low flow estimator representing the most extreme water deficit below normal mean flow. Additionally, this summary statistics table gives the Base Flow Index (BFI) to better quantitatively present a reservoir characteristic for low flow.

Tab. 2.4 Summary statistics for all stations with a daily register (1973-2003) according to climatic regions

climatic region	station	HHQ (m^3/s)	NNQ (m^3/s)	NNQ/MQ (%)	MQ (m^3/s)	Mq ($m^3/s*km^2$)	BFI
Northern Zone	GUATUSO	443	3,8	13,3	28,5	0,11	0,62
Northern Zone	TERRÓN COLORADO	2340	27,7	17,8	155,4	0,08	0,71
Northern Zone	CARIBLANCO	103	1,8	20,7	8,7	0,12	0,72
North Pacific	GUARDIA	812	2,6	10,6	24,6	0,03	0,62
North Pacific	RANCHO REY	156	2	21,5	9,3	0,03	0,72
Central Valley	GUAPINOL	896	1,2	5,7	21	0,10	0,66
Central Valley	TACARES	74	3	27,0	11,1	0,05	0,86
Central Pacific	EL REY	960	1,8	5,8	31	0,05	0,65
Central Pacific	LONDRES	437	3	10,8	27,9	0,13	0,76
Central Pacific	PROVIDENCIA	81	0,6	8,6	7	0,05	0,78
South Pacific	PALMAR	8519	22,1	7,1	311,4	0,07	0,71
South Pacific	CARACUCHO	1454	4,6	6,4	72,2	0,01	0,72
Caribbean	PALOMO	348	4,4	12,2	36	0,10	0,69
Caribbean	ORIENTE	314	4,6	15,7	29,3	0,13	0,67
Caribbean	DOS MONTANAS	777	4,7	8,8	53,6	0,08	0,68
Caribbean	PANDORA	1620	1,3	2,8	46,2	0,07	0,45
Caribbean	BRATSI	2667	11,2	7,2	156	0,07	0,71

Flow regimes

Flow regimes for all available gauging stations over the common period 1973-2003 were derived to obtain a generalised river typing. They mainly depend on regional climate and on catchment's physiography. According to Krasovskaia et al. (1994) the catchment's characteristics, in particular those influencing retention, such as hydrogeology, land use and vegetation coverage account for the variability between basins exposed to similar climatic regimes.

An understanding of streamflow regimes across a region (in this case Costa Rica) is considered very important to define drought and streamflow anomaly, because they demonstrate the normal and expected mean water availability for a year (Stahl, 2001).

Flow regimes are defined as monthly mean discharges normalised by mean flow of the period of record. These monthly indices are also known as Pardé-coefficients (Pardé, 1933). This study classifies regimes at a national scale and uses the generalised climatic regions to describe representative regime types. Hence, it is not expected to find a superposition of regimes from different catchments with different climatic influences. Streamflow is not influenced by snow or ice (glaciers) in Costa Rica, thus they are according to Guilder (1965) and Silva (1991) of a simple pluvial character, but due to precipitation variability of regular or irregular type. Comparisons of flow regimes assigned to the climatic divisions show similar characteristics and therefore support this generalised spatial order (Fig. 2.15).

Simple pluvial flow regimes (Dyck & Peschke, 1995) mainly coincide with precipitation patterns. Catchment's characteristics are presumed to cause departures from expected regime patterns, which are defined as follows:

> *"The Regular Caribbean Type"* (violet colour in Fig. 2.15) at the Caribbean Vertient, where almost the whole year a constant discharge level with only a weak distinction in less streamflow from February until March is guaranteed. There rainfall minus evapotranspiration is nearly equal throughout the year and catchment's aquifers are presumed to be of high storage capacity. This leads to a regime of low streamflow variability, characterised by less emphasised maximum and minimum values. This physiographic influence also explains the deviation from the precipitation regime in October.
>
> *"The Irregular Type"* is bound to the Pacific Vertient with variations showing the climatic phenomenon called "little summer" ("*The Irregular Veranillo Type"*) and the regimes with one peak in October ("*The Irregular Rain Season Type"*). Regimes with a clear distribution in dry and wet months, in the sense of streamflow, are disposed of a sufficient water stage during a varying prolongation of the rainy season with a single peak in October.
>
> This regime type is exposed to a longer summer low flow season. However, *the "Irregular Veranillo Type"* (North Pacific Regime, yellow and South Pacific Regime, white) is characterised by two peaks. A first and weaker one in June and a second main peak in October. The Central Valley Regime (light-blue colour) is balanced by catchment's reservoirs in July and is not characterised by the "little summer" phenomenon of precipitations.

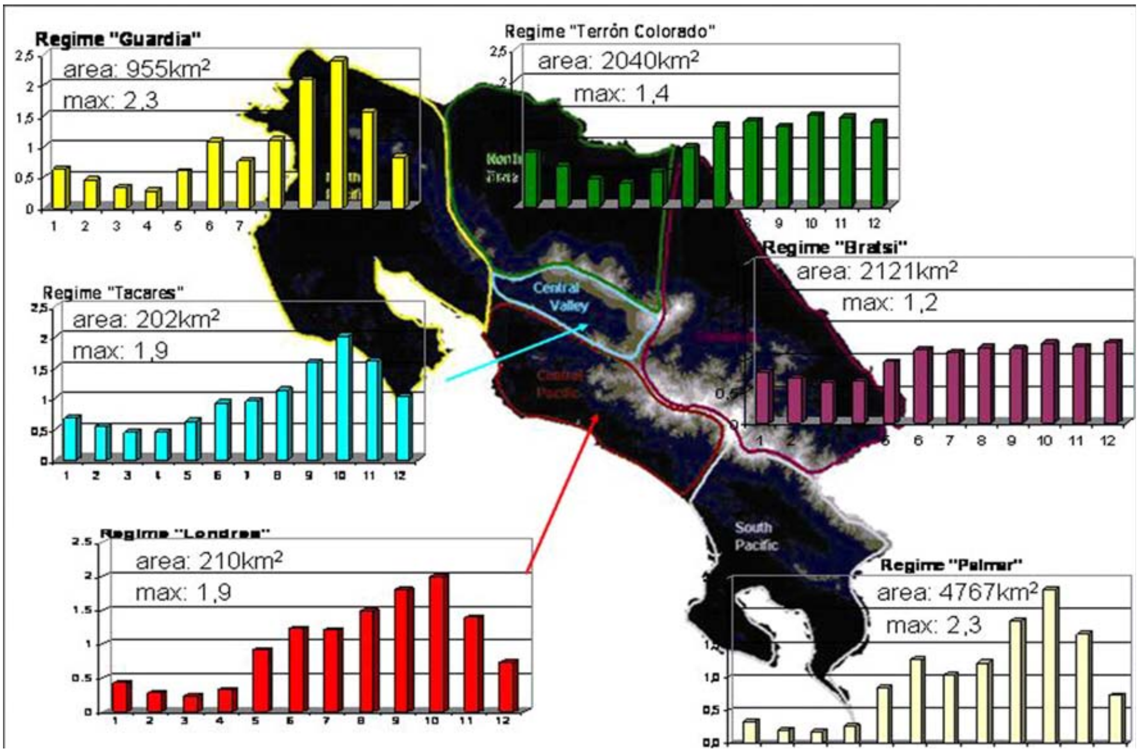


Fig. 2.15 Representative Pardé flow regimes (1973-2003) for a generalised climatic division:

- the North Pacific region: station Guardia
- the Central Valley region: station Tacares
- the Central Pacific region: station Londres
- the South Pacific region: station Palmar
- the Northern Zone region: station Terrón Colorado
- the Caribbean region: station Bratsi

According to Stahl (2001), there are some limitations to the use of monthly mean flows for regime description, because it might be difficult to distinguish regimes, which tend to occur in fewer, more intense flood or drought events. Interannual variability is not included in the definition, either.

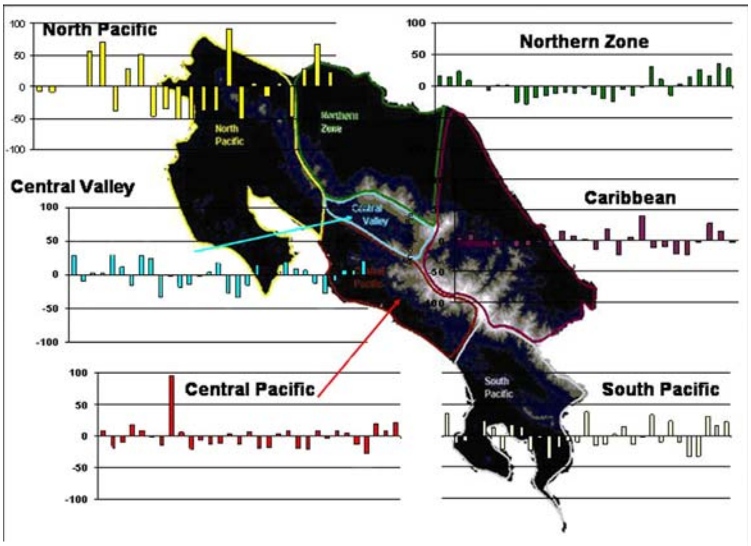


Fig. 2.16 Representative interannual streamflow anomalies (1973-2003) among the regional climates

Low flows

Figure 2.16 shows mean annual deviation tables calculated according to equation (2.1) in order to define annual runoff anomalies for the climatic regions. A closer look has to be taken at the interannual variability of flow regimes and low flow season to be expected across Costa Rica.

These panels are equally presented as anomalies from the mean annual runoff (%) of the period of record from 1973 to 2003 in order to reveal annual variability, which is assumed to be neglected by Pardé flow regimes.
To demonstrate range and units used in the interannual streamflow anomaly figure (Fig. 2.16) following equation is introduced:

$$D_i = \frac{(X_i - \mu_i)}{S_i} \quad \textbf{(2.1)}$$

D_i …Anomaly index for year i (-)
X_i …mean flow for year i (m^3/s)
μ_i …mean annual flow for year i (m^3/s)
S_i …Standard Deviation for year i (-)

The anomaly or deviation from expected mean annual flows is plotted for the calculation period (1973-2003) in terms of discharge deficit (-) or bonus (+) in percentages. This calculation allows detecting annual variability among stations, which might be useful as a drought indicator. Mean annual flows of the North Pacific representative station oscillates around the mean, which is an exception among the other regional climates. Departures over 80 % indicate on the one hand, high dependency on few, intensive and irregular precipitation events, which can be seen in highly variable precipitations during dry season (Fig. 2.12). On the other hand, physiographic characteristics and human influence cannot be neglected.
The other stations generally show less interannual variability than the one of the North Pacific. Less oscillation is to be noted in particular areas, which receive e.g. more annual rainfall quantity and consistency (Caribbean, Northern Zone and South Pacific). Nevertheless, dry years that might not yet be defined as droughts are not only visible in the north of Costa Rica due to precipitation deficits. The temporal resolution of annual means does not satisfy in drought studies; moreover, this analysis of interannual streamflow anomaly should give a brief perception about spatial division of riverflow variability.

Another closer look has to be taken at the innerannual streamflow variability. According to the innerannual precipitation variability regime, (Chapter 2.3.1) similarities in regime patterns are to be expected, which can be seen for nearly all stations. According to Climatology, a higher variability during dry season proves summer as drought season (Fig. 2.12). Figure 2.17 shows the distribution of innerannual streamflow variability regimes (1973-2003) among the regional climatic divisions. The same representative stations selected to display flow regimes (Fig. 2.15) are used in the figure below.

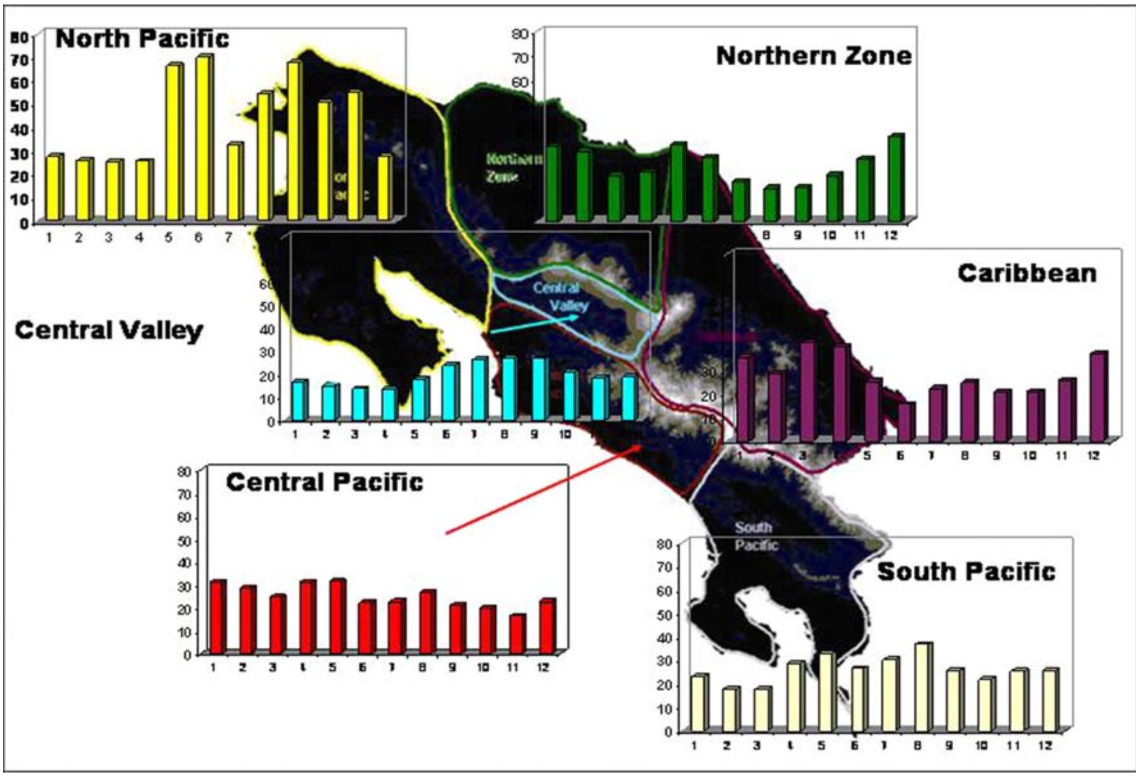


Fig. 2.17 Representative monthly streamflow variability regimes (1973-2003) over a climatic division

In the case of stations, which represent the climatologically regions of the North Pacific and Central Valley, dry season variability seems to be smoothed. This consistent dry season flow indicates a strong role of physiographic characteristics, in particular, those of reservoirs, but does not change summer as expected low flow season. Basin reservoirs completely compensate climate variability and the "Veranillo" effect in July can be recognised (Fig. 2.17). After a long dry period, first intensive rainfalls occurring from May to June are not absorbed by the non-saturated soils. In that region very few natural vegetation coverage exists, which contributes to the rapid transformation into overland flow (Vargas, 2005; personal conversation). This manifests in a high streamflow variability, which decreases with the ongoing rainy season due to rainfalls of lower frequency and more saturated soils. The Northern Zone, Central Pacific and the Caribbean are characterised by higher variability's during low flow season, which coincides with higher monthly precipitation variability's (Fig. 2.12). There natural vegetation coverage and lower storage capacity of reservoirs might play an important role for low flows.

Defining drought season by Pardé flow regimes in terms of typical duration and timing was not considered sufficient, because droughts tend to persist over various months and strongly depend on previous climatic conditions.
According to Young et al. (2000) the calculation of the Q_{95} percentile derived from the flow duration curve (method explained in forthcoming Chapter 3 on Streamflow drought analysis) for the whole period, was found most suited to predefine drought season for further drought analysis.

Seasonality determined by the 95 % percentile, matches in all cases, the beginning of low flow periods indicated by the Pardé flow regimes and innerannual variability regimes, but provoked a significant prolongation of low flow events into the rainy season. This phenomenon is covered due to a lower temporal resolution of monthly means. Generally can be said about flow regimes that they seem to be of an identical seasonality to their respective precipitation regimes, but many regimes are presumed to experience significant modifications due to physiographical characteristics. The latter can be seen in the diminishing “little summer” precipitation pattern (low precipitation period during July) and a change in seasonality of low flows.

Tab. 2.5 Definition of the low flow period for station’s records (1973-2003) according to the Q_{95} percentile

climatic region	station	Q_{95}	low flow period
Northern Zone	GUATUSO	6,3	01.02. - 30.06.
Northern Zone	TERRÓN COLORADO	44,1	01.02. - 30.06.
Northern Zone	CARIBLANCO	2,8	01.01. - 30.06.
North Pacific	GUARDIA	5,1	01.01. - 31.05.
North Pacific	RANCHO REY	3,4	01.02. - 31.07.
Central Valley	GUAPINOL	1,9	01.01. - 30.06.
Central Valley	TACARES	4,2	01.01. - 31.05.
Central Pacific	EL REY	4,1	01.01. - 31.05.
Central Pacific	LONDRES	4,9	01.01. - 30.04.
Central Pacific	PROVIDENCIA	1,6	01.01. - 31.05.
South Pacific	PALMAR	46,8	01.01. - 31.05.
South Pacific	CARACUCHO	14,4	01.01. - 31.05.
Caribbean	PALOMO	9,7	01.01. - 31.05.
Caribbean	ORIENTE	8,7	01.01. - 31.05.
Caribbean	DOS MONTANAS	15,1	01.01. - 31.05.
Caribbean	PANDORA	11	01.12. - 31.05.
Caribbean	BRATSI	52,9	01.11. - 31.05.

Table 2.5 shows predefined low flow seasons for the selected stations and periods (1973-2003), detected when streamflow falls below the Q_{95} percentile (Q_{95} in m^3/s) threshold level. Stations are ordered according to their climatic assignation. Low flow season can be determined for all stations across Costa Rica to mainly occur during dry season.

Typical duration and timing of low streamflows varies in between this summer season, because of different climatological and physiographical catchment’s characteristics. The Caribbean shows from November until May different low flow timings depending on precipitation quantities accumulated in September and October, the months of the lowest rainfall rates (Chapter 2.3.1).

The stations in the Northern Zone experience low flow from the beginning of February until the end of June, which constitute a two month delay after the last intensive rainfalls and a prolongation of more than a month into rainy season. This “recreation” effect show several stations of the Central Valley, Central Pacific and North Pacific, which can be interrelated as a recharge phase of catchment’s reservoirs.

In the case of the Neotropics, it is not possible to define a winter/summer season in the sense of low flows occurring during summer, due to low precipitation and high evapotranspiration and during winter, due to water stored as snow or ice (glaciers). It has to be spoken of winter as a season of increased precipitation rates or also as rainy season. The cause of drought in the tropics has to be seen exclusively in climate variability and human exploitation. Therefore, the definition of the low flow seasons by Q_{95} is used to establish a hydrological year specifically for every streamflow gauging station. The hydrological year starts at the last day of low flow season.

2.4 Summary

This introductory chapter presents an overview of physiographical characteristics of the study area, such as climate, physical geography, geology and finally, hydrology. Typical, general properties of the hydrological cycle and impacting factors of Costa Rica, which can be related to drought, represent an important base for interpretations of resulting drought behaviour. Furthermore, the distinct types of data, such as daily discharge series, monthly precipitation, meteorological and thematic data utilised in this work are introduced.

The drought study is based on 17 streamflow gauging stations with a daily record of at least 20 years representing all major climatic and physiographic regions across Costa Rica. Eleven records cover a common time window from 1973 to 2003 (30 years) and were found the best compromise between a long period of record and a good spatial coverage.

Also available are 18 climate stations with a record from 1950 to 1980 (30 years) of monthly precipitation data to study spatial and temporal variability of rainfall on a national scale. Linking streamflow to atmospheric circulation is carried out with Southern Oscillation indices (e.g. SOI), covering the above mentioned streamflow period of record and is well suited to describe such phenomenon.

Diverse physical geography, geology and surface climatology create, even at a relatively small scale like Costa Rica, different flow regimes. These regimes can be regionally summarised to represent the major topographical and climatological land units. Most of them show a typical pattern of dry and wet season depending on rainfall variation and hydrological storage. A predefining analysis of timing and duration of low flow seasons provides important information for further drought analysis.

3 Streamflow drought

3.1 Concepts of drought

Drought as well as flood is a hydrological extreme and result of natural climate variability considered as natural hazards, which cause temporary impacts on nature and life.

Different socioeconomic standards catch up with natural vulnerability and perceive a drought phenomenon distinctive. This effect of “different drought experience” makes an objective definition difficult (e.g. Yevjevich, 1967, Dracup et al., 1980).
In general, drought is seen as a temporary water deficiency in a particular period and over a particular region and must not be confused with aridity, which is a permanent climate feature (NDMC, 2001).

Droughts can be described from many points of view and due to the lack of a complete definition; the concept of drought through the hydrological cycle seems to be an adequate method (Fig. 3.1).

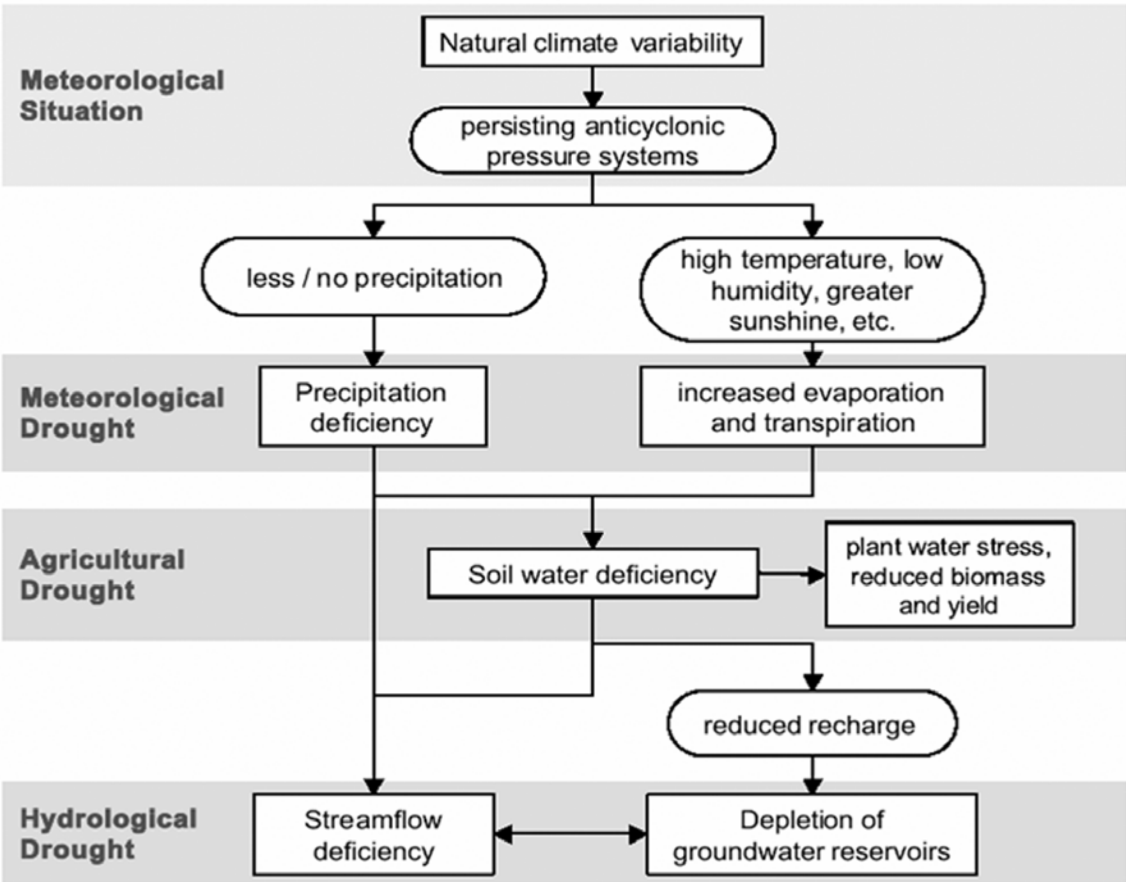


Fig. 3.1 Propagation of drought through the hydrological cycle modified after NDMC (2001)

Particular persistent meteorological situations, such as high pressure systems can cause a precipitation deficit accompanied by high temperature, low humidity and greater radiation input. All this meteorological phenomena are part of natural climate variability and can lead to drought depending on the persistence of the whole system.

Drought in the term of an “abnormal” situation first can be discerned as a precipitation deficit and increased evaporation and transpiration, called *Meteorological Drought*.
If the meteorological situation persists, the lack of atmospheric water can lead to a soil water deficiency, called *Agricultural Drought*. Plant water stress is already characterised by reduced discharge and the depletion of groundwater reservoirs, which cause anomalies in streamflow, defined as *Hydrological Drought*.

The latter is to be investigated on the national scale of Costa Rica, which can be seen as a “summary effect” of natural variation of the hydrological cycle. Furthermore, streamflow deficiency is directly linked to the countries socioeconomic situation. Specially, in a tropical country like Costa Rica, which depends without exception on hydropower for electricity generation and on agriculture for economical well-being, droughts are a major natural hazard.

3.2 Event definition

3.2.1 The threshold level method

Studying streamflow drought requires an adequate statistical method to define droughts or streamflow deficiencies. The threshold level method is usefully applied in many investigations on drought. The threshold is defined as a particular discharge value, which can be exceeded or non-exceeded (Fig. 3.2). An event starts, when the discharge falls below the threshold and ends when either the threshold level is exceeded by flow or water deficit volume below the threshold has been replenished.

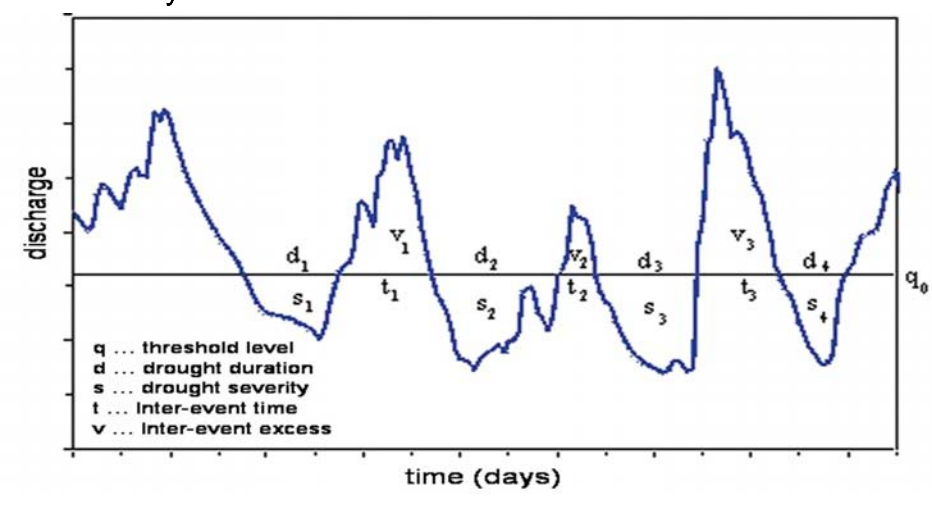


Fig. 3.2 Drought event definition by a threshold level applied on a daily discharge hydrograph from (ARIDE homepage on www.uni-freiburg.de/forsch/aride/)

Yevjevich (1967), who analysed time series by the statistical theory of runs, first applied this concept in hydrological drought research. Parameters of the runs below the threshold are the run-length (drought duration, d_i) and run-sum (deficit volume or severity, s_i). In this study, these Parameters are used to characterise drought at different gauging stations.

For hydrological design problems these drought parameters are often derived to analyse frequency in order to obtain recurrence intervals of droughts of certain duration and severity (Chapter 4.2.4 on Drought risk). Furthermore, other studies model time series of run parameters as a stochastic process and an overview is given in Tallaksen & van Lanen (2004).

This work presents the threshold level method to determine historic drought events of the last 30 years at Costa Rican gauging stations. These events are the basis to study temporal and spatial drought behaviour using derivates of drought duration and deficit volume as indices (see Chapter 3.3 on streamflow drought indices).

Drought definition requires the choice of a threshold level, which can be constant or varying over time. Depending on the annual flow regime, droughts can be analysed separately by a constant threshold for the whole year or by a seasonal constant value, for instance summer and winter seasonal threshold (Tallaksen, 1997; Stahl, 2001).

If the annual regime is considered the “normal” situation, then a monthly or daily varying threshold (panels b) and c) in Fig.3.3) should be applied to determine streamflow deficiencies (Stahl, 2001). In the case of Costa Rica the annual regime is divided into a consistent high flow and low flow season, which is considered an inner annual seasonality and according to Tallaksen & Hisdal (1997) best represented by a constant seasonal threshold (panel a) in Fig. 3.3).

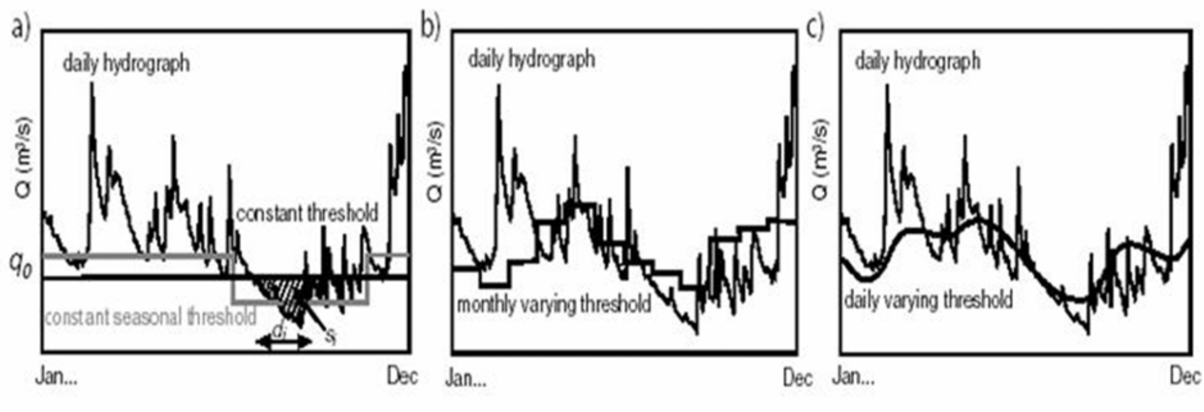


Fig. 3.3 Different threshold levels (Stahl, 2001):
- constant and constant seasonal threshold
- monthly varying threshold
- daily varying threshold

Stahl (2001) not automatically considers discharge below the threshold level as drought, not until a certain defined period remaining below the threshold is reached, which causes a certain deficit volume. Moreover, such minor drought events should be defined as streamflow deficiencies rather than streamflow droughts. Details on the choice of the threshold level, its derivation and application on particular problems of the study are given in the following Chapter 3.2.2 Streamflow drought – the constant threshold level.

3.2.2 Streamflow drought – the constant threshold level

A threshold level can be a particular streamflow, which should not be exceeded (non-exceeded) for design purpose, guaranteeing a certain level of streamflow for navigation, ecological habitats (e.g. ecological minimum discharge) or hydropower generation. Nevertheless, it has to be decided of how to derive the threshold level for different applications. A valid method is to calculate statistical values from the long-term hydrograph of a streamflow gauging station (Demuth, 1993). Possible parameters are e.g. extreme values (Mean Annual Minimum flow, MAM) of a specific season or period of time or a percentile from the flow duration curve (fdc) most commonly used in drought studies. The fdc is the complement of the cumulative distribution function of daily, weekly, monthly streamflow or of any other time interval (Vogel & Fennessey, 1994).

The dependence of percentiles derived from the fdc on catchment area shows Figure 3.4 on the left. Storage capacity is reflected in exceedance probability and clearly coincides with catchment size (R^2 = 0,73). This is assumed to demonstrate the physiographical influence of aquifer properties on low flow and drought, as long as superposition of different flow regimes in the same catchment can be neglected (Tallaksen & van Lanen, 2004).

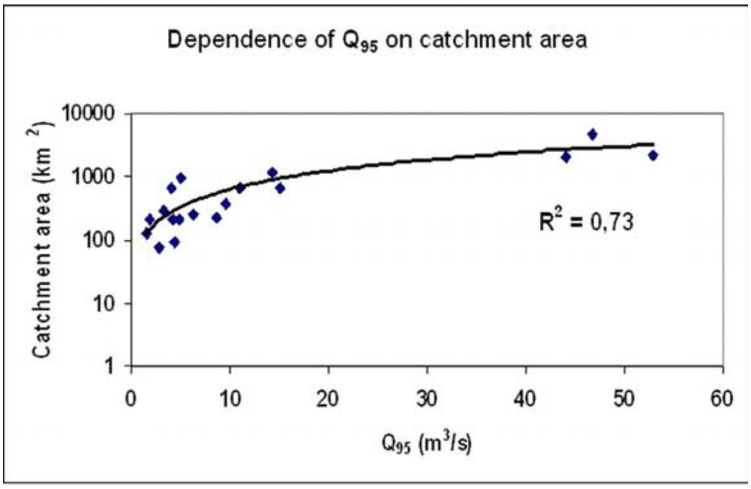


Fig. 3.4 Dependence of Q_{95} on catchment area (log-scale)

Figure 3.5 shows the plotted flow (*Q* in m³/s) versus the corresponding flow exceedance frequency, a dimensionless index that expresses the proportion of time that a specified daily flow is equalled or exceeded during the considered period (Gustard et al., 1992) of two contrary stations. Both stations, Tacares and Guapinol are situated in the same climatic region (Central Valley) and are of comparable catchment areas (202 km^2 and 203 km^2).

Tacares shows a moderate flow duration curve of little slope, while station Guapinol exhibits a more flashy behaviour due to higher maximum values, lower minimum values and a steeper sloped curve. These contrary characteristics reflect storage capacities of a hydrological catchment, which can be found in their specific exceedance percentiles, such as the Q_{95} (compare Q_{95} values of both stations given under the panels of Figure 3.5).

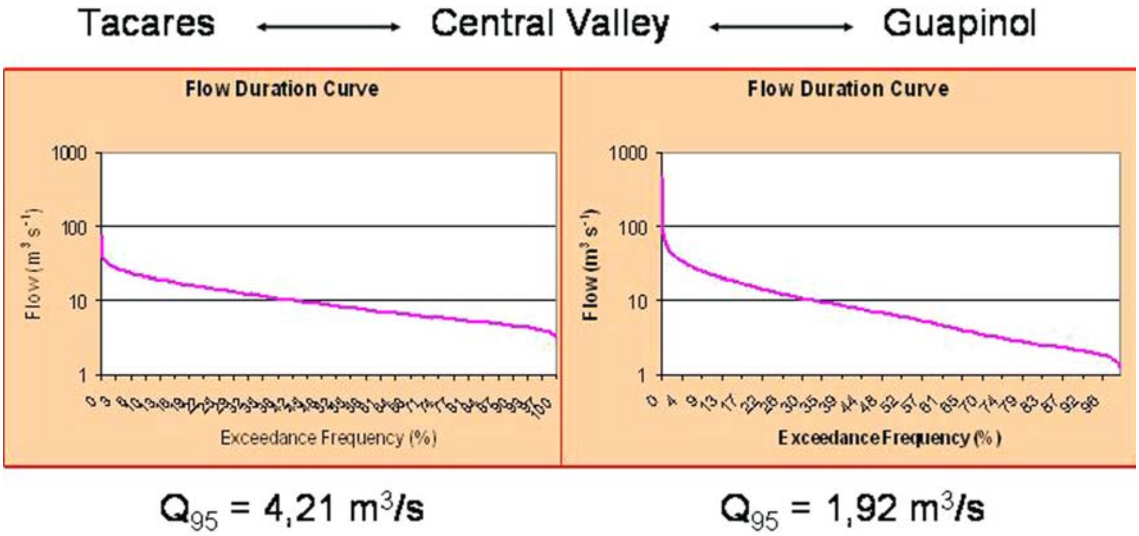


Fig. 3.5 Flow duration curve of the period 1973-2003 for two stations (Tacares and Guapinol) of the same climatic region with their specific Q_{95} percentiles

When percentiles of the fdc are to be determined as threshold levels, their time resolution must be considered in terms of purpose and climatic region. This study is carried out in the Neotropics, which are characterised by flow regimes of relatively low interannual variability (Chapter 2.3.2) connected to a seasonal division into high and low flow period of relatively high innerannual variability. However, a daily time resolution was chosen for this study to represent the Neotropical flow regime characteristics. All regime types included, are that of perennial rivers excluding zero flow, which makes low threshold levels (Q_{70} and Q_{90} of the whole period of record were applied) reasonable. Due to the strong seasonality, droughts mainly occur during summer or low flow season, which was preliminarily defined as hydrological year in order to not separate drought events. In some regions of Costa Rica, dry season is experienced as a natural situation and only a deviation from the "normal" low flow can be defined as drought.

Therefore, it was considered adequate to apply a seasonal constant threshold level to detect streamflow deviations during both high and low flow season, because lower than normal flows during high flow season ("recharge season") might be important for later drought development. A hydrological summer drought (dry season is generally considered summer in Costa Rica) is principally considered to be caused by climate variability producing less precipitation during dry and rainy season, which might not recharge sufficiently reservoirs to maintain a certain streamflow level during low flow season.

Figure 3.6 shows the constant period of record Q_{90}, Q_{70} and the constant seasonal Q_{90} and Q_{70} threshold level applied on a Costa Rican daily streamflow hydrograph and demonstrates the seasonality phenomenon mentioned above.

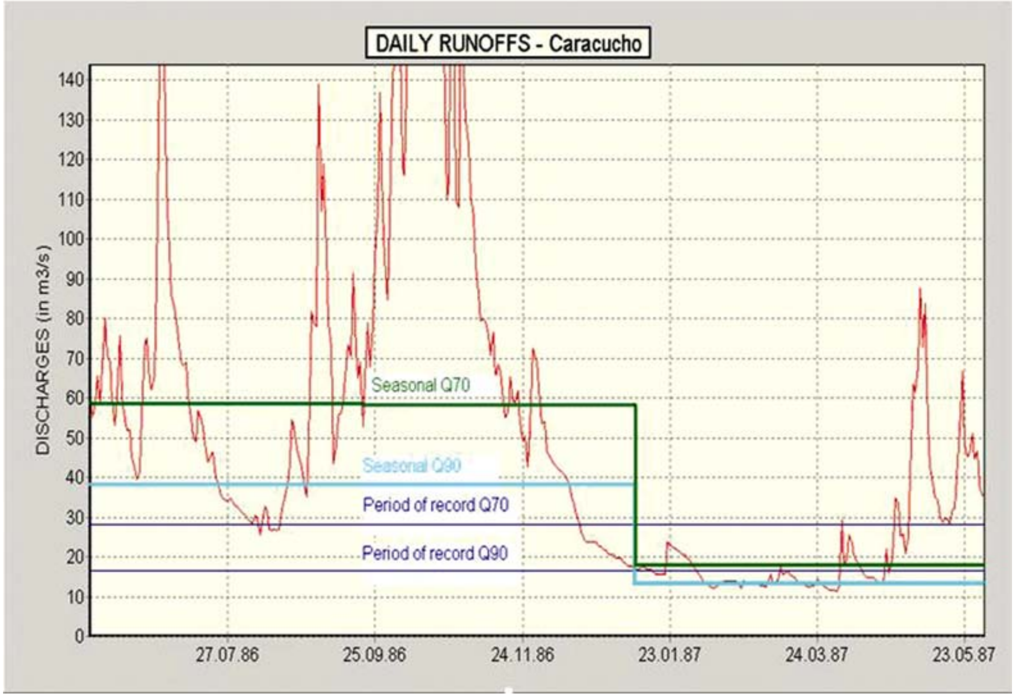


Fig. 3.6 Daily discharge hydrograph of the hydrological year 1986/87, station "Caracucho" with constant threshold levels

It can be noticed, that streamflow deficiencies during low flow season are well detected by a constant threshold level (Q_{90}), but deviations during rainy season maintain unrevealed. Seasonal constant threshold levels were defined to detect most sensitively streamflow anomalies among both high and low flow season. Such detected events conform to the requirements of previously mentioned drought definitions and in that manner, it is considered adequate to talk about streamflow deficiencies (Stahl, 2001). Seasonal Q_{70} seems appropriate for the analysis of both seasons as it increases information quantity in terms of the number, duration and deficit volume of drought events and decreases the number of minor droughts. The threshold levels *period of record Q_{90}* and *seasonal Q_{70}* were found to be the best compromise for detecting sensitively streamflow anomalies of rainy and dry season.

Furthermore, there are years for which streamflow never falls below the threshold, they are called "zero drought years". These years without a defined drought might affect further extreme value analysis and are to be set minimal by applying a seasonal threshold as done with the Q_{70}. Another advantage can be observed by comparing the different thresholds displayed in Figure 3.6. The number of minor droughts exceeding the threshold for a very short period of time and dividing a large drought in several mutually dependent droughts can be decreased. This procedure follows general recommendations on the use of different threshold levels in drought studies provided by Tallaksen et al. (1997). Table 3.1 of the seasonal threshold levels for all stations can be found under Appendix.

3.3 Streamflow drought indices

3.3.1 Annual Maximum Duration (AMD)

The annual maximum duration in days is a streamflow drought index selected from all droughts derived by NIZOWKA for certain threshold levels and pooling features. This study uses, as mentioned before (Chapter 3.2) the Q_{90} constant period of record threshold and the Q_{70} seasonal constant threshold to investigate temporal and spatial drought behaviour.

Before calculating all indices, the threshold levels should be verified to justify their application. This is done by comparing statistics of different thresholds and their resulting drought indices. The Q_{70} constant period of record threshold was used additionally to calculate the AMD. Focusing on the constant Q_{90} AMD's, many zero drought years can be revealed, which are, for most of the years filled by the constant Q_{70} AMD's. Significant inter-event excesses are hereby neglected by connecting smaller droughts to a large one spanning low flow season. The Q_{70} constant threshold level can be considered as too "coarse" and little sensitive. The seasonal constant threshold level approach seems to be justified in this study, because increases information quantity of the statistics e.g. in terms of less zero flow years and higher means. An overview is presented in the following table (Tab. 3.2) showing the statistics of distinctively obtained AMD's for the period of record (1973-2003) for an example station.

Tab. 3.2 Station "Guatuso" AMD statistics for different thresholds

threshold	mean AMD	S	max.	zero drought	minor droughts <10days
Q_{90} all year	28,7	22,1	98	6	2
Q_{70} all year	86,4	34,8	135	1	0
Q_{70} low flow season	34	25	105	5	2
Q_{70} high flow season	19,5	10,3	46	1	5

The statistics tables show the mean AMD, the standard deviation S, the maximum value, the number of zero drought years and the number of minor droughts (less than 10 days) for the discriminated threshold levels. As mentioned above it can be seen that for the constant Q_{70} seasonal threshold compared to the non-seasonal Q_{90} level information amount of the statistical parameters such as e.g. the mean increases. The mean AMD for Q_{70} low flow season increases from 28,7 days (Q_{90} annual threshold) to 34 days and the number of zero droughts decreases from six to five.

The drought index "Annual Maximum Duration" (AMD) was calculated for all available streamflow stations of Costa Rica, even those with less than 30 years of register, but a minimum of 20 years to provide as much information as possible for further temporal and spatial drought behaviour studies. A complete statistics table (Tab. 3.3) of all derived drought indices for all stations is given under "Appendix".

3.3.2 Annual Cumulated Duration (ACD)

The “Annual Cumulated Drought Duration” (ACD) is the sum of all derived streamflow drought durations by a certain threshold level and so completely describes a drought situation over a defined period of time or season.

A maximum drought might occur registered by a maximum index (e.g. AMD, AMV), which is followed by an unregistered minor drought and additionally increases the impact on the already weak eco- and social system. The latter minor event is registered by the cumulated indices, which should not be neglected. The statistics table below (Tab. 3.4) gives a general perception of the ACD derived from different threshold levels and in comparison with the maximum duration index. It can be seen that the maximum ACD and AMD are the same, which indicates one single event. The ACD mean value is higher than the maximum index, contains as many zero years as the AMD and reduces the number of minor events.

Tab. 3.4 Station “Guatuso” ACD statistics for different thresholds of the period 1973-2003

threshold	mean ACD	S	max.	zero drought	minor droughts <10days
Q_{90} all year	34,3	24,8	98	6	2
Q_{70} all year	107,1	31,3	151	0	0
Q_{70} low flow season	41,4	26,7	105	4	1
Q_{70} high flow season	35,8	22,5	104	1	3

3.3.3 Annual Maximum Deficit Volume (AMV)

The drought index “Annual Maximum Deficit Volume” (AMV) is derived from the NIZOWKA “deficit volume” result selecting the annual maximum events. These are normalised by the mean flow of streamflow registers to guarantee spatial comparability for further studies (Jakubowski, 2003). An example of AMV statistics (Tab. 3.5) similar to the AMD index is given below.

Tab. 3.5 Station “Guatuso” AMV statistics for different thresholds of the period 1973-2003

threshold	mean AMV	S	max.	minor drought <50*1000s
Q_{90} all year	102,5	97,5	449	6
Q_{70} all year	1490,6	668,8	2425	0
Q_{70} low flow season	168,3	144,4	656	4
Q_{70} high flow season	356,1	655,6	1318	1

The AMV unit is in “1000 seconds”, because of the normalisation by mean flow (m^3/s). The number of zero drought years is the same as in the AMD table and substituted here, by a minor drought volume limit set equal to 50 (1000s), which decreases from 6 (Q_{90} all year) to 4 (Q_{70} low flow season).

In General, the difference between the drought indices derived by the constant and the seasonal constant threshold level is clearly distinguishable, but in what relation to each other stand the different indices AMD and AMV. A simple linear correlation of both indices shows a strong temporal relationship (r ~ 95 %), which means that they are mainly governed by the same hydrogeographical effects like climate variability and physiographic factors. However, according to Tallaksen & Hisdal (1997) it is to presume, that the extreme values of deficit volume (AMV) are more related to catchment's characteristics than these of duration (AMD).

3.3.4 Annual Cumulated Deficit Volume (ACV)

This drought index summarises all derived drought deficit volumes during a certain defined period of time or season to a cumulated loss of water volume. This drought index represents, in other words, a quantitative tool for drought studies in specific geographical regions and is very useful to study regional spatial drought characteristics. Compared with the Annual Maximum Deficit Volume it can be seen, in contrary to the AMD/ACD comparison, an increase in the registered maximum drought events. Generally, the same characteristic relation between the mean values and standard deviations exists (Tab. 3.6).

Tab. 3.6 Station "Guatuso" ACV statistics for different thresholds of the period 1973-2003

threshold	mean ACV	S	max.	minor droughts $<50*1000m^3$
Q_{90} all year	117	107	449	4
Q_{70} all year	1712	712	3614	0
Q_{70} low flow season	209	195	681	4
Q_{70} high flow season	583	458	2081	1

3.3.5 Number of droughts (ND)

The drought index "Number of Droughts" (ND) represents the annually or seasonally occurring amount of droughts in the term of drought frequency. It can be a useful parameter to detect if whether streamflow drought has become more or less frequent. Table 3.7 shows the main statistics such as mean, standard deviation and maximum. The already mentioned general characteristics of different threshold levels are also reflected in the ND index.

Tab. 3.7 Station "Guatuso" ND statistica for different thresholds of the period 1973-2003

threshold	mean ND	S	max.
Q_{90} all year	1,2	0,75	2
Q_{70} all year	2,4	1,1	6
Q_{70} low flow season	1,3	0,75	2
Q_{70} high flow season	2,7	1,6	4

3.4 Summary

This chapter introduces different concepts of drought and its prospection through the hydrological cycle. Although this work studies the behaviour of hydrological drought across Costa Rican streamflows, drought development at different temporal and spatial scales must be kept in mind for interpretation. Furthermore, an adequate drought event definition implemented in this study by the threshold level method is presented and used to compute several drought indices.

Typical flow regimes of the climatic and geographic region under study are characterised by its strong seasonality. A clear division into a low and high flow season lead to the application of a seasonal constant threshold level obtained by the seasonally separated percentiles of the respective flow duration curves (fdc).

This seasonality can be seen to represent normality of a typical Neotropical regime, thus it was considered unnecessary to derive drought indices by a daily varying threshold level. However, it would be interesting to compare the obtained results from the seasonal constant threshold with a monthly varying threshold level, because seasonality varies on a monthly base from one station to another. The fdc itself shows variability and dependency on the period of record used. According to Vogel & Fennessey (1994), the fdc would be better represented by confidence intervals calculated from the seasonal fdc's of each individual year of the period of record.

In this study, just the hydrological year for each station was individually defined in order to avoid the separation of one drought into two single events. Moreover, the drought indices obtained from the seasonal constant threshold were compared in all studies to the indices from the non-seasonal constant threshold. The low and high flow drought indices were found to be adequate to detect more sensible streamflow drought behaviour, nevertheless, the non-seasonal indices particularly obtained from the Q_{90} threshold level represent a useful tool e.g. for trend analysis in drought series.

Five different drought indices were chosen to satisfy different purposes of this drought study, the number of droughts (ND) occurring during a year, the maximum drought indices for duration and deficit volume (AMD and AMV) and the cumulated drought indices for duration and deficit volume (ACD and ACV).

The latter cumulated indices represent all drought events occurring during a defined period of time or season and can not be neglected for seasonal drought anomaly study, because small events following a severe drought even aggravate the socioeconomic situation of the affected region and are not reflected by annual maximum indices.

4 Temporal and spatial behaviour of streamflow drought

4.1 Temporal dynamics of streamflow droughts

To study the temporal behaviour of droughts several aspects are investigated;

a) the derivation of dry and wet years for the common period 1973-2003 displayed by all stations across Costa Rica

b) the persistence of drought for possible sequences of dry and wet years in terms of overall indices and single stations

c) the seasonal occurrence of drought in terms of innerseasonal high flow dynamics and the interseasonal relation between low and high flow season.

4.1.1 Evaluation of dry or wet years

The temporal behaviour of droughts is studied by evaluating the “dryness” or “wetness” of single years for all stations in order to calculate the overall maximum drought indices of AMD and AMV. Implemented into this study are eleven stations with the common period 1973-2003. Overall indices are computed by summarising the annual maximum parameters (AMD, AMV) of all eleven stations for each year. Zero drought years were taken into account. The results for the overall AMD’s and AMV’s are presented in Figure 4.1. Overall indices exceeding the mean overall parameter can be considered as dry years, such with values falling below the mean as wet years. The overall maximum indices (AMD and AMV) are derived from the Q_{90} annual constant threshold and from the Q_{70} low flow seasonal threshold to show, possible differences and are according to Demuth & Heinrich (1997) considered an appropriate method to study temporal drought behaviour.

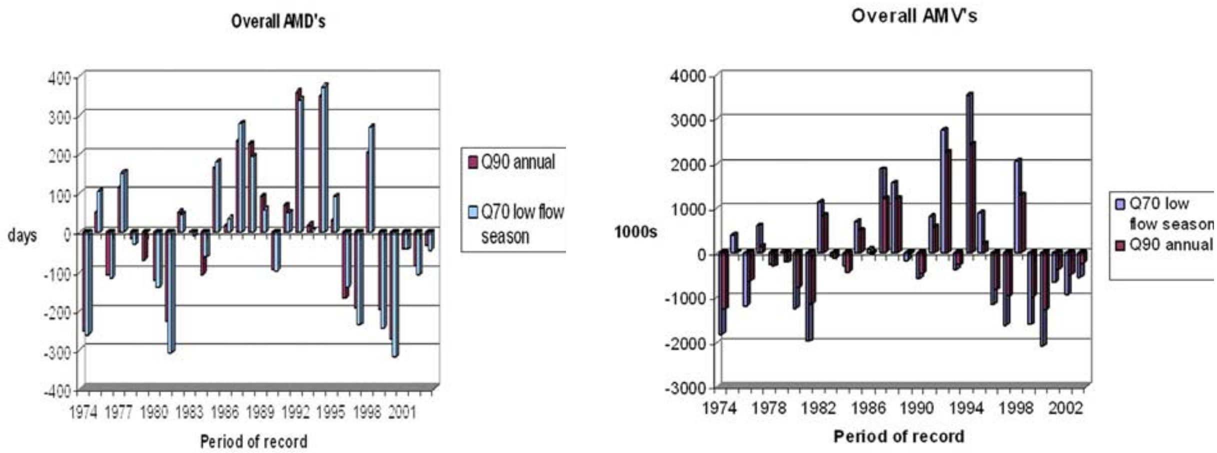


Fig. 4.1 Overall calculations summarised over all stations for the period 1973-2003:
- Overall AMD’s derived by Q_{90} annual and Q_{70} low flow season threshold for the period 1973-2003 and Overall AMV’s derived by Q_{90} annual and Q_{70} low flow season threshold for the period 1973-2003

The mean value for the annual Q_{90} overall AMD's accounts for 293 days (Fig. 4.1 left panel), the AMV's for 2450 (1000s) (Fig. 4.1 right panel), the Q_{70} low flow season overall AMD's for 392 days and the AMV's for 2253 (1000s). The mean overall parameters are set in Figure 4.1 equal to zero to better display the division into dry (positive) and wet years (negative).

Figure 4.1 reveals the same years of maximum values for the annual Q_{90} overall AMD's (653 days) in 1992, for the AMV's 3777 (1000s) in 1994, for the Q_{70} low flow season overall AMD's (765 days) in 1994 and for the AMV's 5786 (1000s) also in 1994. The years 1992 and 1994 lie very close together and make a distinction difficult, but they undoubtedly represent the maximum drought years in terms of duration and deficit volume. A clear distinction of minimum values reveals the year 2000 as the "wettest" year in terms of duration and deficit volume. Furthermore, from Figure 4.1 can be noticed that dry and wet years seem to cluster for certain periods (dry sequences: 1985-1989 and 1991-1995).

Slight deviations between the different indices and thresholds can be noticed in Table 4.1. The annual Q_{90} AMD (produces lower index values) puts one single dry year (1983) on the list, wether the AMV's tend to neglect dry years in the sequences (1986 and 1993). Generally, it can be said that these "deviation years" are very close to their mean values and so difficult to distinguish into dry or wet overall conditions.

Table 4.1 shows the division into overall dry (in red colour) and wet (in blue colour) years.

Tab. 4.1 Overall dry (red) and wet (blue) years for the common period 1973-2003

Q_{90} all year AMD	1973	1974	1975	1976	1977	1978	1979	1980	1981	1982	1983	1984	1985	1986
Q_{90} all year AMV	1973	1974	1975	1976	1977	1978	1979	1980	1981	1982	1983	1984	1985	1986
Q_{70} low flow AMD	1973	1974	1975	1976	1977	1978	1979	1980	1981	1982	1983	1984	1985	1986
Q_{70} low flow AMV	1973	1974	1975	1976	1977	1978	1979	1980	1981	1982	1983	1984	1985	1986
Q_{90} all year AMD	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000
Q_{90} all year AMV	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000
Q_{70} low flow AMD	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000
Q_{70} low flow AMV	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000
Q_{90} all year AMD	2001	2002	2003											
Q_{90} all year AMV	2001	2002	2003											
Q_{70} low flow AMD	2001	2002	2003											
Q_{70} low flow AMV	2001	2002	2003											

4.1.2 Persistence of droughts

Sequences of annual maximum droughts over several years indicate persistence in drought behaviour. It is very likely, that droughts exhibit persistency, because they depend on many feedback mechanisms. If they did not, according to Beran & Rodier (1985) there scarcely would be an impact on man's activity.

Persistence is caused by a long memory in the system, such as a large storage, which can be e.g. a groundwater reservoir. This memory is mainly influenced by catchment's characteristics such as groundwater storage capacities, soil properties and a strong climatic seasonality.

Costa Rica is dominated by a strong seasonality in flow and precipitation regimes and catchments are partly connected to large reservoirs, which can be assumed to provoke persistency. In general, droughts or streamflow deficiencies can be expected to be persistent at various time-scales due to influencing factors, such as very large, slowly reacting aquifer systems, regional climate variability and long-term climatic fluctuations, such as the El Niño-Southern Oscillation (ENSO) (Stahl, 2001). This fluctuations influence sea-surface temperatures and are reportedly associated with droughts in the region (Ramirez, 1992; Glantz & Ramirez, 1996; Waylen et al., 1997), which will be investigated in further chapters (Chapter 5).

In fact, in this study another time-scale of the persistency phenomenon is under investigation, namely the interannual persistent behaviour or in other words, multi-year droughts. Multi-year droughts in the tropics must be well distinguished from those in arid regions lasting several years. A definition approach for the Neotropics includes a seasonal transition in order that developed dry season droughts last among high flow season without severity to appear again in the following low flow season.

A useful tool to detect such phenomenon is the autocorrelation function or coefficient r (k):

$$r(k) = \frac{\sum_{i=0}^{N-1} (x_i - \mu)(x_{i+k} - \mu)}{\sum_{i=0}^{N-1} (x_i - \mu)^2} \quad \textbf{(4.0)}$$

N … time series (-)

N-1 … resulting autocorrelation time series or "correlogram" (-)

μ … mean of the series (-)

x_i … value of time series (-)

x_{i+k} … x_i at k time steps later (-)

This coefficient r (k) measures the degree of a linear correlation between the observations at a time and the observations at k time steps later. The lag-one autocorrelation coefficient r (1) is a simple measure of the time dependence for time series. The autocorrelation for a given time lag is considered not to be significantly different from zero if it is inside the confidence limits for a given significance level α. A time series can be assumed to be independent only if 1 - α of the autocorrelation coefficients r (k) for k ≥ 1 are found to be non-significant (Tallaksen & van Lanen, 2004).

Then the time series is also assumed to be approximately normal distributed and stationary. According to the theory of persistence, a time lag of one year and a significance level of α = 0,05 (confidence interval of 95 %) for the statistical t-Student test were chosen to study time dependence among the overall drought indices.

For both overall drought indices summarised across all stations (Chapter 4.1.1, non-seasonal AMD and AMV) and their different derivates (seasonal indices) autocorrelation indices with a time lag of one year were computed. The results are displayed in Figure 4.2 and can be presumed to be of non-persistent interannual drought behaviour. The autocorrelation coefficients do not exceed 40 % and the t-test results assume the coefficients not to be significantly different from zero between its confidence limits.

The r (1) displayed in Figure 4.2 for both, overall AMD's (left panel of Fig. 4.2) and AMV's (right panel of Fig. 4.2) show the same oscillation starting with an increasing negative correlation, continued by its maximum value and a decreasing into a negative correlation. Demuth & Heinrich (1997) found autocorrelation coefficients under 50 % to be sufficient to prove non-interannual persistency. The statistical test results confirm this argumentation.

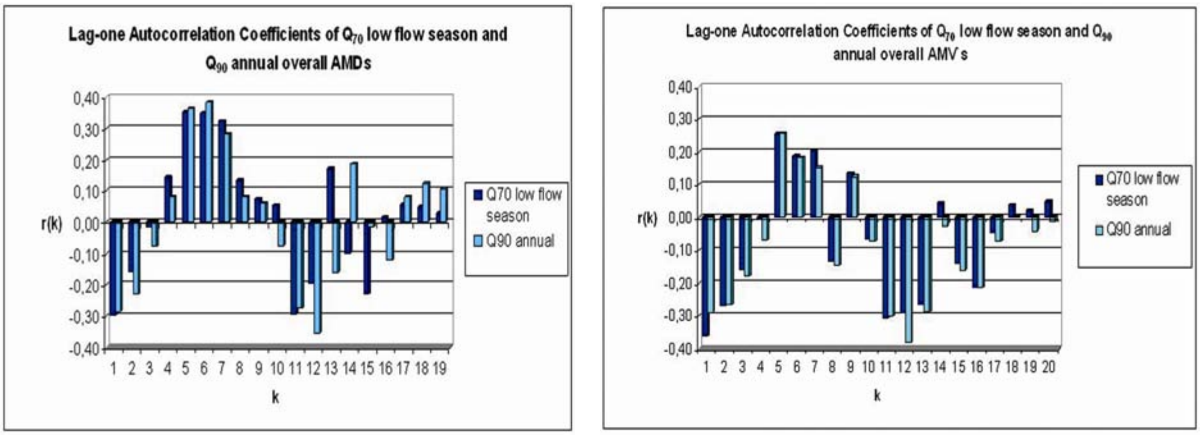


Fig. 4.2 r (1) autocorrelation coefficients for AMD and AMV overall calculations:
- r (1) series of overall AMD's summarised across all stations (Q_{90} annual and Q_{70} low flow season) for the common period 1973-2003 and
- series of r (1) overall AMV's summarised across all stations (seasonal and non-seasonal for 1973-2003)

The overall drought indices do not show interannual drought persistence, but the summarising calculation of the overall indices might mask single persistent phenomena. The AMD series for each single station were selected to perform a time dependence study according to the introduced equation **(4.0)** and resulting maximum autocorrelation coefficients r (1) are displayed across the study area to demonstrate a spatial pattern of stations showing persistency in their annual maximum series.

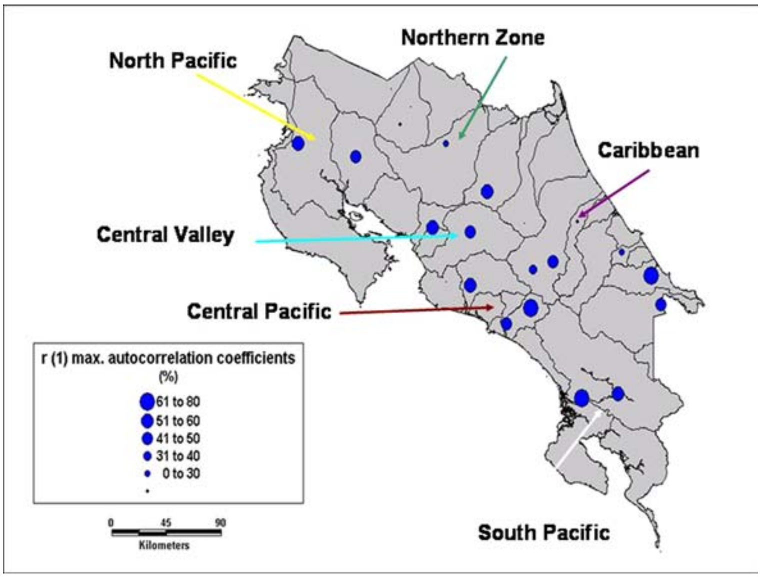


Fig. 4.3 Maximum autocorrelation coefficients r (1) across Costa Rican major climatic regions displayed as varying sized dots representing each single station.

Figure 4.3 clearly shows single stations (see legend) that contain tendencies for multi-year droughts in the sense of seasonal dependency. Four stations at the Pacific and one at the Caribbean of maximum r (1) over 50 % are assumed to exhibit a persistent tendency.

This is partly confirmed by statistical test results, which are not significantly different from the mean in between a wider confidence interval of 90 % (significance level, α = 0,1) than usually applied (95 %). Station "Palmar" at the South Pacific Ocean delta of river "Grande de Terraba" shows the maximum value of 73 %.

This station stands for the largest catchment with an area of almost 5000 km^2 covering nearly the whole South Pacific region. It is to presume, that very large aquifers play an important role on multi-year drought persistence of this station. Furthermore, the confluence of two large rivers inside the catchment is assumed to result in a persisting hydrological memory. Station "Guardia" located in the North Pacific region is affected by the same reservoir capacities as station "Palmar".

4.1.3 Seasonal occurrence of droughts

Analysing the seasonality of drought requires a definition of seasons, which was preliminarily done by flow and precipitation regime typing and the definition of the station-specific hydrological year. The seasonal occurrence of droughts can be assessed by analysing drought events separated into each season (LF-HF, Tab. 4.2), by studying innerseasonal drought behaviour as e.g. for high flow season (Tab. 4.3) and by the interrelation of seasons (Fig. 4.6).

Seasonality can be visualised by plotting a seasonally separated daily discharge record (1973-2003) for one example station into low and high flow season (Fig. 4.4). Generally can be said that Costa Rica is characterised by two different types of streamflow droughts:

- Minor droughts of short duration and high deficit volumes seem to cluster during rainy or high flow season.
- Major droughts of long duration and low deficit volumes span the low flow season.

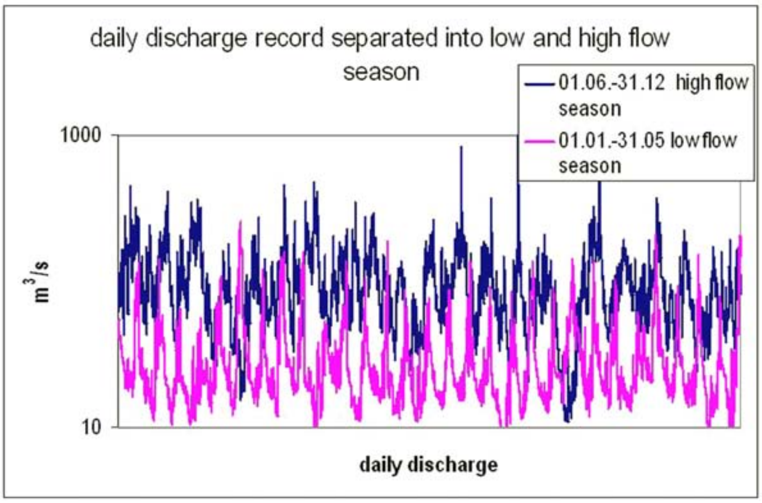


Fig. 4.4 Daily discharge record (1973-2003) of an example station seasonally separated into low and high flow season (logarithmic scale)

Table 4.2 compares the seasonal (LF-low flow season, HF-high flow season) mean drought indices (AMD, AMV and ND-Number of droughts) of each single station according to their climatic region, respectively to prove the hypothesis of two general drought types. Furthermore, the standard deviation is given to verify the mean values in the term of variability. The seasonal mean drought indices are displayed in red. The mean AMD low flow season index always exceeds the corresponding high flow index. In terms of deficit volume and number of droughts this fact turns to the contrary clearly proving the general seasonal drought typing.

Tab. 4.2 Seasonal drought indices of one representative station according to climatic regions

climatic region	station	threshold	mean AMD	S	mean AMV	S	mean ND	S
Northern Zone	Guatuso	Q_{90} annual	35,6	18,4	127,1	93,1	1,2	0,7
		Q_{70} LF	40,5	21,4	194,1	138	1,3	0,8
		Q_{70} HF	20,1	9,7	367,9	292,9	2,7	1,6
North Pacific	Guardía	Q_{90} annual	32,2	33,7	142,3	189,6	0,8	0,9
		Q_{70} LF	39,2	36	220	258,2	0,9	0,8
		Q_{70} HF	17,9	18,5	180,6	204,3	1,7	1,6
Central Valley	Tacares	Q_{90} annual	27,5	29,9	132,9	187,9	1,2	1,2
		Q_{70} LF	42,6	35,2	252,9	294,8	1,3	0,8
		Q_{70} HF	23,4	24,1	384	565	1	0,7
Central Pacific	Londres	Q_{90} annual	28,3	25,2	94,7	118,9	1,4	1,1
		Q_{70} LF	28,3	25,2	94,7	118,9	1,4	1,1
		Q_{70} HF	15,3	17,8	275,3	369	1,2	1,0
South Pacific	Caracucho	Q_{90} annual	25,9	23,7	94,3	123,9	1,6	1,0
		Q_{70} LF	34,4	26,7	138,9	152,1	1,7	0,9
		Q_{70} HF	28	22,5	571,8	583	1,8	1,0
Caribbean	Pandora	Q_{90} annual	20,9	18,2	104,5	110,3	1,9	1,6
		Q_{70} LF	34,1	28	267,8	253,9	1,9	1,3
		Q_{70} HF	18,3	12,6	420,2	396,3	2,7	1,5

Inter- and innerseasonal drought occurrence

To detect possible differences in temporal drought behaviour a constant seasonal threshold level was chosen. High flow season can be seen as major recharge season recuperating deficits of the preceding low flow season and providing reservoirs for the connected dry season. Climate variability such as less precipitation mainly affects that recharge causing a prolongation of drought duration and severe water deficiencies.

A closer look has to be taken at drought occurrence patterns during high flow season to better understand its role for low flow season droughts. According to the precipitation regimes of distinct climatic regions (see Fig. 2.12) Costa Rican wet season is characterised by natural heterogeneous climate effects like the short period (around two weeks) of decreased precipitations called “little summer” in July, intensive rainfalls during the first months of high flow season (May, June) and by months of the highest precipitation rates (August until November, except for the Caribbean). Rainfall deficiencies during that period of high flow season may directly lead into a streamflow drought.

Table 4.3 shows the temporal distribution of high flow season drought events. Representative stations were taken to characterise the climatic regions in terms of occurrence of the little summer phenomenon in typical flow regimes, the total number of drought events and the major events of longer than 20 days duration. These events were selected for their occurrence before and from August in order to reveal an innerseasonal pattern, which might be related to drought development.

Tab. 4.3 High flow seasonal drought event distribution across climatic regions for:
- total events > 20 days
- events > 20 days from August
- events > 20 days before August

climatic region	little summer	total	events >20d	events from August >20d	events before August >20d
North Pacific	yes	57	17	17	0
Central Valley	no	31	16	6	10
Central Pacific	yes	36	8	2	6
South Pacific	yes	51	20	3	17
Northern Zone	no	71	25	18	7
Caribbean	no	81	15	10	5

Table 4.3 clearly shows a majority of minor events during high flow season, except for the representative station of the Central Valley, where more than half of all drought events is of more than twenty days duration. These twenty days duration were taken as limit to separate events before August from those starting in August. The division reflecting events before August are considered to contain a possible prolongation of preceding low flow season drought and a decrease in streamflow due to the little summer phenomenon.

Events starting in August are assumed to affect the major recharge period from August until November, except for the Caribbean region, where the months of September, October show the lowest precipitation rates throughout the year.

The most extreme example shows the station for the North Pacific region, where low flow season ends in July. In fact, all drought events during high flow season affect the period of the highest precipitation rates. The other Pacific regions reveal more events before August, which is generally assumed not to contradict mentioned assumptions. Some events start before August, but remarkably persist into the recharge period. Generally, can be said that the maximum events in the term of duration occur from August until November or start earlier and persist into these months.

A majority of longer events occurring from August until November clearly reveals the Northern Zone and the Caribbean as interseasonally connected. The latter region is difficult to classify into the approach of determining the cause for drought development due to generally higher precipitation rates throughout the year. The Northern Zone confirms the hypothesis revealing all major events from August until November, which are the months of the highest precipitation rates in that region.

Anomaly indices

Some regions of Costa Rica experience streamflow drought in the term of streamflow deficiency during dry season as a natural situation and the population adapted several methods like wells and water storages to maintain their daily water supply. To distinguish between water deficiency and drought events, a seasonal anomaly index was introduced based on the deviation from the mean annual cumulated drought index in percent. The mean ACD or ACV is assumed to represent the natural experienced streamflow drought during the station specific defined season.

The derivation of the seasonal drought index is given in the following equation:

$$D_{ij} = \frac{\left(X_{ij} - \mu_{ij}\right)}{S_j} \qquad \textbf{(4.1)}$$

D_{ij} …seasonal drought anomaly index (-)

X_{ij} …drought index for year i and season j (-)

μ_j …mean drought index for season j (-)

S_j …standard deviation of drought index for season j (-)

According to the mentioned procedure above seasonal anomaly indices were calculated for all stations separated into their predefined low and high flow season (see also Table 4.4 under Appendix).

The following interpretations are to be referred to the climatic region represented by one example station. This dimensionless index offers great opportunities to compare stations and their representative catchments of different climatic and physiographic characteristics to evaluate its seasonal threat to droughts. Based on the period of record's mean drought duration or deficit volume, earlier defined as natural drought experience, the Anomaly Index reflects drought severity and can be used to determine different levels of severity. For that purpose, a scale from –4 to +4 is introduced assigning different anomaly values to a certain severity level. It has to be taken into account that minus two in most of the cases already represents a zero drought year. This can be referred exclusively to this study and period of record used. Other studies in different regions with longer record series might contain lower levels and require the scale proposed here.

Anomaly Index severity level:

- 4	**no consequences**
- 3	**slight drought experience**
- 2	**little drought experience**
- 1	**moderate drought experience**
0	**normal drought experience**
+ 1	**severe drought**
+ 2	**abnormally severe drought**
+ 3	**excessively severe drought**
+ 4	**extreme severe drought**

The following figure (Fig. 4.5) gives an example of the ACD/ACV dry season Anomaly Index for the common period 1973-2003 of the station "Caracucho" according to the drought severity scale.

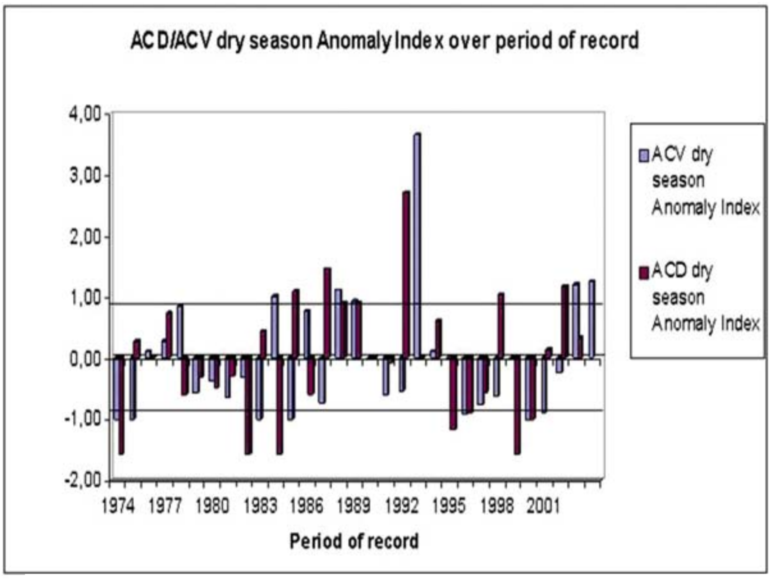


Fig. 4.5 ACD/ACV dry season anomaly index of station Caracucho (South Pacific region) for the period of record (1973-2003)

This should give a perception of two different drought indices. Both indices generally follow the same interannual distribution. The example (Fig. 4.5) reveals a 1992 maximum event of over 300 % deviation from the mean value, which was a reportedly severe drought event in that region.

Talking about severity, very few extreme events, which exceed a level of plus one and represent a real threat to the socioeconomic of the corresponding region, can be observed. As mentioned above on the section about persistency, a sequence of severe droughts can be observed from 1987 to 1989 indicating a multi-year drought in the sense of seasonal transition.

This type of seasonality obviously does not present droughts lasting for several years, but a certain dependency of low flow season droughts from one season over high flow season to another dry season can be presumed. The autocorrelation coefficients for the example station do not exceed 50 %, for what station “Caracucho” is declared to be of non-persistent behaviour.

The fact, that both anomaly indices follow the same temporal pattern, does not conclude for their distribution in magnitude. The ACV Anomaly Index significantly exceeds the ACD Anomaly Index for the same year and non-exceeds it for another year. An example can be given for the 1992 maximum anomaly, where the ACV index superates the ACD anomaly for over 80 %. In other cases some years (1989, 1998) show a considerably severe ACD hazard, but without any sign of the cumulated volume exceeding the mean natural drought limit.

This can be explained in the nature of the different drought indices, because the deficit volume index corresponds according to Tallaksen & Hisdal (1997) more to physiographic characteristics than to climate variability, while the duration index is less afflicted by catchment’s properties than by climate patterns. In fact, both indices can be assumed to properly reflect the drought situation and if any of these drought anomaly indices reaches a level near the mean value, the hazard of socioeconomic impacts is likely given.

After interpreting anomaly characteristics for two different indices, a comparison of seasonality should follow. The selected stations were found to represent best the average behaviour for the distinct climatic regions. The ACV anomaly index is separated into its low (LF-dark red) and high flow (HF-light blue) season (Fig. 4.6), in order to detect a seasonal relationship for better understanding a possible influence of wet season on severe dry season droughts.

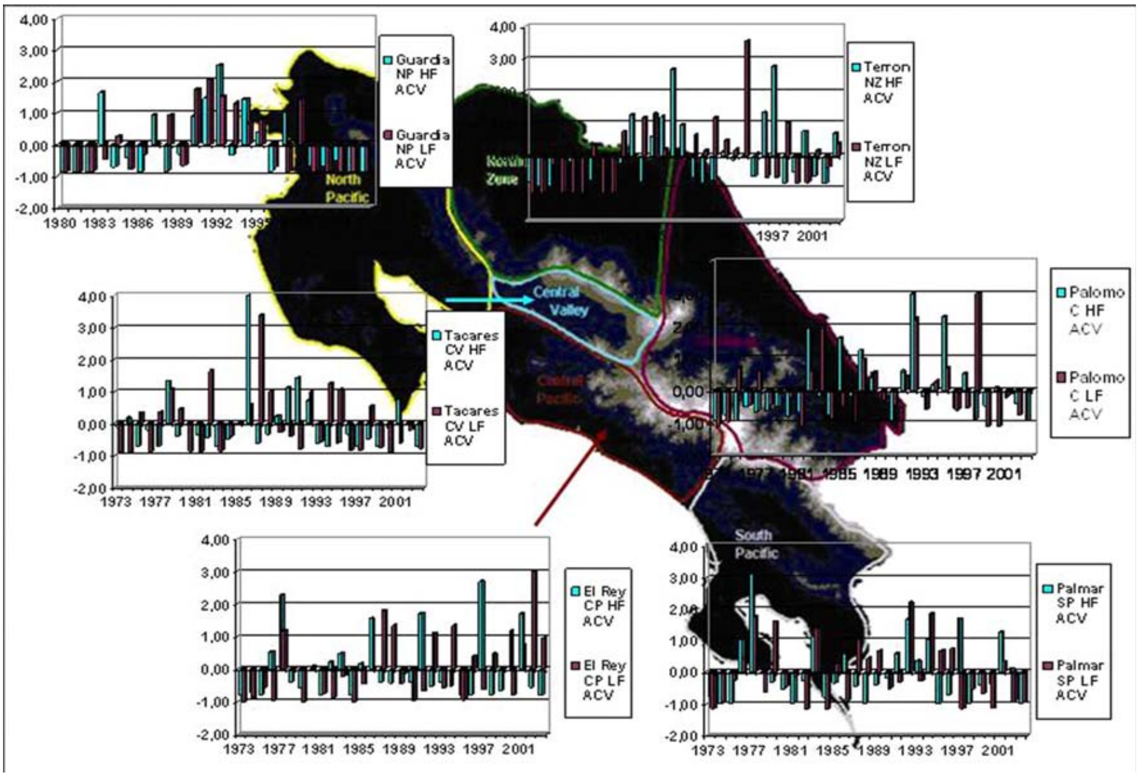


Fig. 4.6 Comparison of the seasonal (HF, LF) ACV's for representative stations of the climatic division over the common period 1973-2003:

- The North Pacific region:	station Guardia
- The Northern Zone region:	station Terrón Colorado
- The Central Valley region:	station Tacares
- The Central Pacific region:	station El Rey
- The South Pacific region:	station Palmar
- The Caribbean region:	station Palomo

Derived high flow season droughts are assumed to influence low flow season droughts depending on the quality of recharge. A strong relation in the course of seasonal droughts (interseasonal behaviour) can be taken from the Figure 4.6.

Figure 4.6 clearly shows a high flow season drought is followed by a severe low flow season drought for the years (1976/77, 1982/83, 1986/87, 1991/92, 1997/98 and 2001/02) in the case of the South Pacific region, the North Pacific region and the Caribbean. The Northern Zone region shows no detectable interseasonal relation, while the Central Valley and the Central Pacific experience such relation varying from year to year.

It has to be taken into account that the high flow season droughts of reference occurred one year before the mentioned dry season drought, but are displayed in Figure 4.6 for the same year. The negative value -1,52 reflects a zero drought year for the low flow season and the value -1,4 a zero high flow season drought year. A maximum high flow season drought does not always lead to a maximum low flow drought event.

Even though, seasonally events are not always followed or preceded by an ongoing or foregoing drought. Quantity in the drought magnitude varies from season to season leaving other possible causes of drought development open.

4.1.4 Conclusions on temporal drought behaviour

Temporal dynamics of streamflow droughts in Costa Rica are investigated at an interannual and innerannual scale. Overall, maximum drought indices were derived to evaluate a general distribution of dry and wet years for the period of record (1973-2003). Part of this study was also to test different indices obtained from different threshold levels.

It can be said, that the overall calculations for different indices (AMD, AMV) follow an identical temporal oscillation pattern into dry and wet years. Sequences of droughts over several years were discovered and led to the assumption of a persistent tendency in the system.

The lag-one autocorrelation coefficients r (1) are utilised to detect such persistency. The r (1) did not exceed a value of 50 % and due to the results of a statistical t- test, the overall series summarised across all stations were found to be of non-persistent behaviour. The same autocorrelation study was realised for the maximum series (AMD, AMV) of each single station, because the calculation of the overall series is supposed to mask single persistency phenomena.

This investigation revealed several stations (Palmar, Guardia, Pandora and Providencia) mainly situated at the Pacific Vertient, which partly show strong dependency on time. Causes can be explained, at first, by large slowly reacting reservoirs and, second, by long-term atmospheric fluctuations, such as e.g. ENSO.

The innerannual scale of streamflow droughts is investigated by their seasonal occurrence and the results show two general types of droughts in Costa Rica. It can be spoken of short droughts with major deficit volumes that cluster during wet season and of long droughts with minor deficit volumes that span dry season.

An anomaly index for the cumulated durations and deficit volumes was developed to better study severity of droughts. This brought up the hypothesis, that the preceding high flow situation plays an important role on influencing low flow season drought. A regional comparison of high versus low flow season ACV's confirmed such theory for the South Pacific region, the North Pacific region and the Caribbean.

4.2 Spatial behaviour of streamflow droughts

To study the spatial behaviour of droughts several aspects are investigated;

a) the regional distribution of maximum droughts is assumed to reveal a first spatial pattern of the most affected areas by drought in the term of maximum drought duration

b) the spatial variability of drought in terms of drought susceptibility for duration and deficit volume

c) the regional development of seasonally occurring droughts in terms of anomaly duration and deficit volume indices over a dry period of years and

d) the spatial drought risk in terms of seasonally estimated magnitudes of different indices and different return periods.

4.2.1 Regional distribution of maximum drought indices

Clear temporal drought behaviour could be revealed, but how are that temporal characteristics reflected over a diverse, geographical region like Costa Rica.

For that purpose, various methods try to evaluate regional streamflow drought behaviour. This section separates the absolute maximum drought indices (AMD) to find spatial patterns across the climatic regions defined in Chapter 2. Results are assessed in Figure 4.7 by regionally demonstrating the years of the maximum drought occurring and in Table 4.5 by summarising the maximum drought events. The stations and their maximum years respectively are distinctively displayed to better visualise the regional character of maximum droughts (see legend of Figure 4.7).

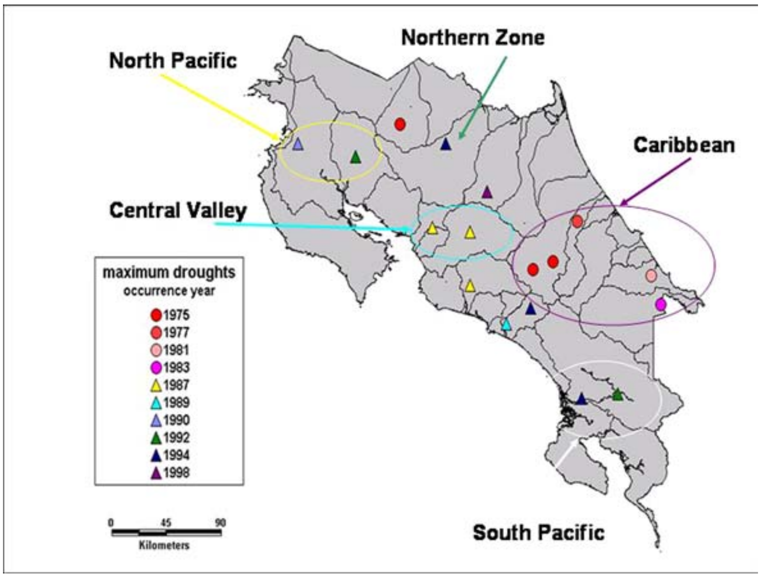


Fig. 4.7 Maximum drought events separated for occurring years and climatic regions

Figure 4.7 shows that stations of the same climatic region seem to be remarkably clustered at a specific period of time (e.g. the Central Valley and the Caribbean region). The most extreme example shows both stations of the Central Valley with their absolute maximum drought duration at the same time (1987).

The Central Pacific stations cluster at the same period (1987 and 1989), as well as the South Pacific stations (1992 and 1994), the North Pacific stations (1990 and 1992) and the Caribbean (1975 until 1983). The maximum values of the Northern Zone stations are spread over the whole period of record with two consecutive years in 1994 and 1998.

If a closer look at the climatic division of Pacific and Atlantic Ocean is taken, the strong separation of maximum events is a remarkable feature. The 70's and early 80's are characterised by maximum drought durations at the Caribbean Vertient (red dots), while the end of the 80's and 90's are manifested by maximum droughts at the Pacific Vertient (triangles). This generally gives a first perception of spatial drought patterns.

The following table shows the different predefined climatic regions, how many streamflow stations belong to that region, the year of the maximum drought occurring and the value of the register's maximum AMD for the low flow seasonal threshold. Table 4.5 shows a distribution of maximum droughts similar to the evaluated overall dry years. Exceptions are the years 1977 and 1990, which are according to the temporal drought behaviour study (Chapter 4.1), not considered as dry years.

Tab. 4.5 Q_{70} low flow seasonal absolute maximum AMD's across climatic regions

	number of	**AMD**									
climatic region	**stations**	**1975**	**1977**	**1981**	**1983**	**1987**	**1989**	**1990**	**1992**	**1994**	**1998**
Northern Zone	3	108								117	105
North Pacific	2							95	127		
Central Valley	2					85;131					
Central Pacific	3					89	84			95	
South Pacific	2								120	82	
Caribbean	5	64;94	80	104	108						

4.2.2 Spatial variability indices

A variability index was developed to assess how susceptible a catchment is to drought, because it can be said, that the higher the value for variability is, the more afflicted to extreme droughts is the station. An increase in deviation from the mean drought index, such as AMD or AMV, results in higher variability indices, expressed as the ratio of standard deviation through 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. A result table (Tab. 4.6) is given below.

Figure (Fig. 4.8) shows the seasonal (HF, LF) and non-seasonal (Q_{90}) variability coefficients for the Annual Maximum Durations (AMD) and Annual Maximum Deficit Volumes (AMV). Colour blue reflects low variability (< 100 %), while colour green stands for a variability of around 100 % and red signals the highest variability (> 130 %). The AMD calculations follow the same spatial pattern as the AMV variability indices. In general, a clear division between the Pacific and Caribbean Vertient can be seen. The different indices vary considerably in magnitude as it can be noticed from the legend in Figure 4.8. An identical scale from 70 % to 150 % was chosen to guarantee comparability. Please note that the upper panel of Figure 4.8 displays the stations respectively to their climatic region in order to give an overview about locations. Variability indices are regionalised by the IDW interpolation method exclusively for displaying spatial patterns of drought affliction and must not be utilised for further calculations.

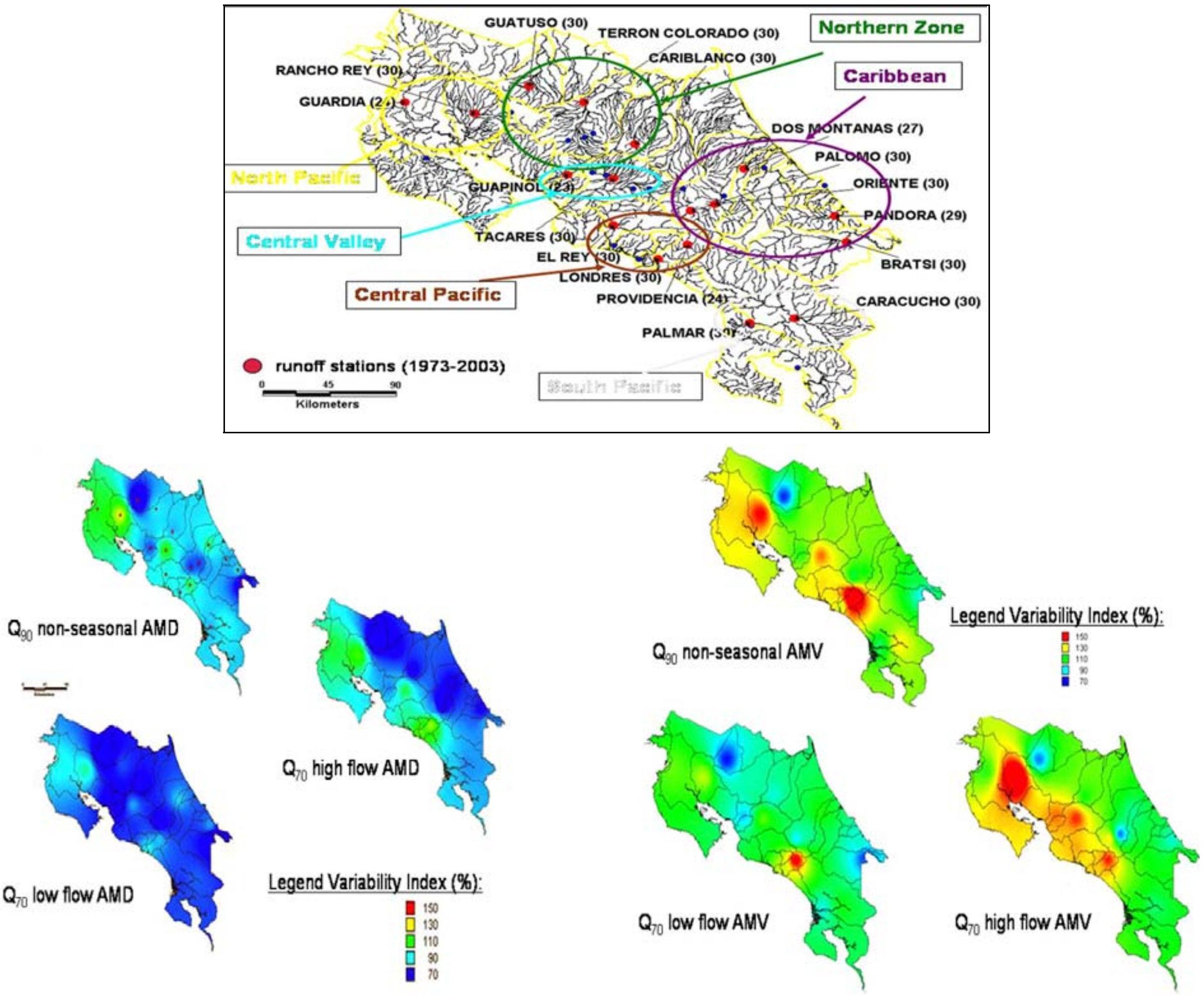


Fig. 4.8 Regionalised variability coefficients for the period 1973-2003 of AMD (left panel) and AMV (right panel) for:
- Q_{90} non-seasonal
- Q_{70} low flow seasonal
- Q_{70} high flow seasonal threshold levels

All three calculations of Figure 4.8 reveal the North and Central Pacific as the most afflicted regions to extreme droughts, while the western part of the Northern Zone and the Caribbean show the lowest affliction. Table 4.6 gives the results for each station to better interpret variability indices across the climatic divisions. The maximum and minimum values of each result column are respectively marked in red and blue colour.

Tab. 4.6 The statistics of variability coefficients for different drought indices

variability indices (%):				LF		HF	
climatic region	**station**	**Q_{90} AMD**	**Q_{90} AMV**	**Q_{70} AMD**	**Q_{70} AMV**	**Q_{70} AMD**	**Q_{70} AMV**
Northern Zone	GUATUSO	51,7	73,3	52,8	71,1	48,0	79,6
Northern Zone	TERRON COLORADO	88,6	120	76,1	97,65	67,4	115,6
Northern Zone	CARIBLANCO	84	119,3	65,7	93,42	65,6	110,9
North Pacific	GUARDIA	104,8	133,2	91,8	117,36	103,4	113,1
North Pacific	RANCHO REY	127,2	151,7	96,9	124	113,9	178,9
Central Valley	GUAPINOL	76,6	112,1	56,7	85,47	80,2	141,2
Central Valley	TACARES	109,1	141,4	82,6	116,57	102,9	147,1
Central Pacific	EL REY	92,1	133,1	73,5	106,19	97,3	136,6
Central Pacific	LONDRES	89,1	125,6	89,1	125,55	116,3	134,0
Central Pacific	PROVIDENCIA	101,3	189,6	85,3	157,06	122,1	148,0
South Pacific	PALMAR	84,6	103,3	74,4	93,05	85,3	110,8
South Pacific	CARACUCHO	91,5	131,4	77,6	109,5	80,4	101,9
Caribbean	PALOMO	73,9	104	62,3	88,26	80,9	129,9
Caribbean	ORIENTE	74,8	110,1	71,6	98,15	51,3	78,5
Caribbean	DOS MONTANAS	97,2	118,2	86,2	111,79	67,8	99,6
Caribbean	PANDORA	87,4	105,6	82,1	94,81	68,9	94,3
Caribbean	BRATSI	61,2	90,6	54,6	75,59	83,3	111,1
μ:		87,9	121,3	75,3	103,8	84,4	119,5
S:		17,4	25,1	12,9	20,3	21,4	25,5
r:		0,80		0,81		0,82	

Table 4.6 and Figure 4.8 obviously reveal station “Guatuso” (Northern Zone) as the lowest afflicted catchment for neither extreme drought durations nor extreme deficit volumes. North Pacific station “Rancho Rey” is highly exposed to extreme droughts characterised by non-seasonal and seasonal AMD maximum variability. The maximum deficit volume variability shows station “Providencia” situated at the Central Pacific as the most susceptible station to streamflow drought. These stations seem to be bound to one single drought index, but a closer look demonstrates a highly correlated behaviour of AMD and AMV indices. This means, that a high AMD variability coefficient coincides with a high value of AMV variability, as well as to the contrary (Tab. 4.6: r ~ 0,80). Table 4.6 shows remarkably higher AMV variability coefficients compared to the AMD series. The latter variability index register contains a maximum value of 127 %, while the maximum AMV variability index reaches 190 %.

Both mentioned maximum variability values count for the Q_{90} non-seasonal series and exceed the seasonal index series. The Q_{70} low flow seasonal maximum variability values are 97 % for the AMD and 157 % for the AMV index. The high flow seasonal maximums just lay in between the two others. Temporal drought characteristics are reflected in the difference of variability among low and high flow season, in the way that more variable droughts of short duration seem to cluster in wet season, while droughts that are more consistent dominate spanning dry season. This fact reveals the AMV as a more variable index, sensible to light changes in the system. The very low standard deviation of the variability coefficients (Tab. 4.6) points towards little spatial diversity, which concludes for the interpretation in between the climatic divisions.

The Q_{90} AMD derived by the 90 % non-seasonal percentile threshold level generally demonstrates higher variability coefficients for the regions afflicted to extreme events, particularly the South Pacific and the northern Caribbean seem to be far more exposed to extreme durations than for the Q_{70} low flow calculation. This fact can be seen as a result of the methodology used, because non-seasonal thresholds represent a less sensitive method to detect streamflow droughts due to the rejection of seasonality in flow regimes.

4.2.3 Seasonal anomaly indices mapping

Different anomaly indices for ACD and ACV were taken to study the regional drought behaviour over a defined period of time. A spatial picture of the situation or severity of a special year and season can be obtained by displaying these indices across the geographic regions of Costa Rica. A sequence of dry years (1991-1995) revealed by the overall calculations (Chapter 4.1.1) was chosen to demonstrate spatial patterns over a relatively dry period of years. A complete table (1991-1995) of the statistics for the ACD anomaly indices (Tab. 4.4) is presented under Appendix.

The anomaly indices obtained for the low flow season obviously contain less variability than those obtained for high flow season due to their lower standard deviations (Tab. 4.4). Furthermore, the anomalies of the ACD low flow season vary less than those of the ACV low flow season. The years 1992 and 1994 are revealed as the most affected by severe droughts due to anomaly indices exceeding a level of plus one. The mean high flow season anomaly values are significantly lower and present the years 1991 and 1992 as the most affected. Figure 4.9 displays the regionalised 1991-1995 drought sequence for the low flow season ACV, which perfectly reflects the spatial variability of regional drought development at various temporal scales. An appearing abnormally severe drought ($D > 2$) at the west of the North Pacific region in 1991 moves on clearly separated from the Northern Zone further east in 1992. When in 1993 a severe drought in the Northern Zone is developing, one year later the whole North to the Caribbean is covered by an extreme severe drought. In 1995, the drought situation seems to relax, while a severe drought moved to the southernmost point of the Caribbean.

Besides the drought movement, the North Pacific and Northern Zone maintain a constantly high severity level over the complete sequence revealing these regions as the most affected by streamflow drought in terms of duration and deficit volume anomalies.

Figure 4.9 presents the spatially visualised temporal sequence (1991-1995) of cumulated deficit volume anomalies (D) for low flow season.

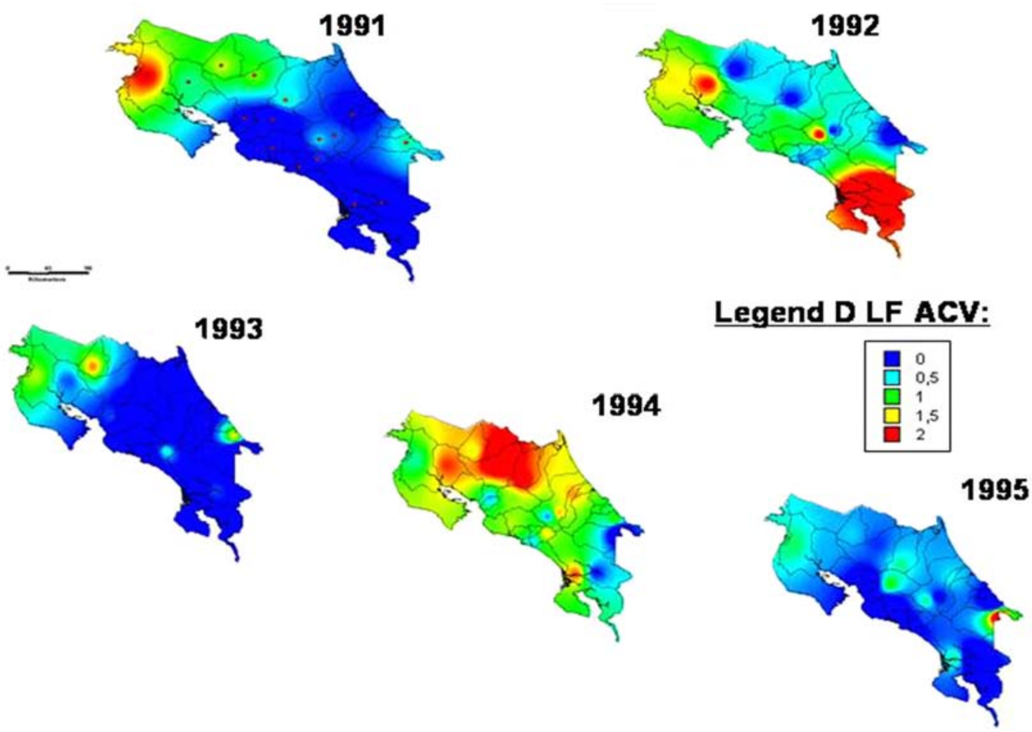


Fig. 4.9 ACV low flow seasonal (LF) anomaly index (D) over drought sequence (1991-1995)

The 1994 low flow season can be seen as a period of extreme drought in terms of drought duration and deficit volume across most parts of Costa Rica. The drought centre moves to the Northern Zone, and except two stations of lower anomaly, the whole country is expanded by streamflow drought of more than a factor 1-severity level. In the year 1995, the situation seems to ease from the south. Severity drops to more moderate levels in the north, where the Northern Zone keeps the cross as a drought centre.

Furthermore, a certain drought movement of some regions can be observed analysing this sequence of five years. The region of the North Pacific is every single year of this period affected by drought, while the most severe drought centres move from the very west of that region eastwards to threat the Northern Zone and even the northern Caribbean. To the contrary, all other stations show at least once during that sequence of dry years a severe drought, but due to more variability, the situation returns more easily back to normality.

This points to interpret, that obviously the north of Costa Rica is the most affected region by streamflow droughts in the term of drought duration and severity and zooming into this geographical division the North Pacific region goes ahead of the Northern Zone.The ACD seasonal anomaly index confirms this hypothesis of regional drought development in the term of streamflow drought duration and an identical spatial picture as for the ACV LF can be observed in the Figure 4.10 for the deficit volume anomalies over the proposed time sequence.

According to the study on temporal drought patterns (Chapter 4.1) high flow seasonal behaviour is assumed to play an important role on drought development and manifestation during low flow season. Merely spatial visualisation of the high flow seasonal ACV anomalies was derived (IDW) to demonstrate the drought movement and relation to its dry season counterparts over the sequence 1991-1995. The regionalised ACV high flow seasonal anomalies (D) sequence is presented in Figure 4.10.

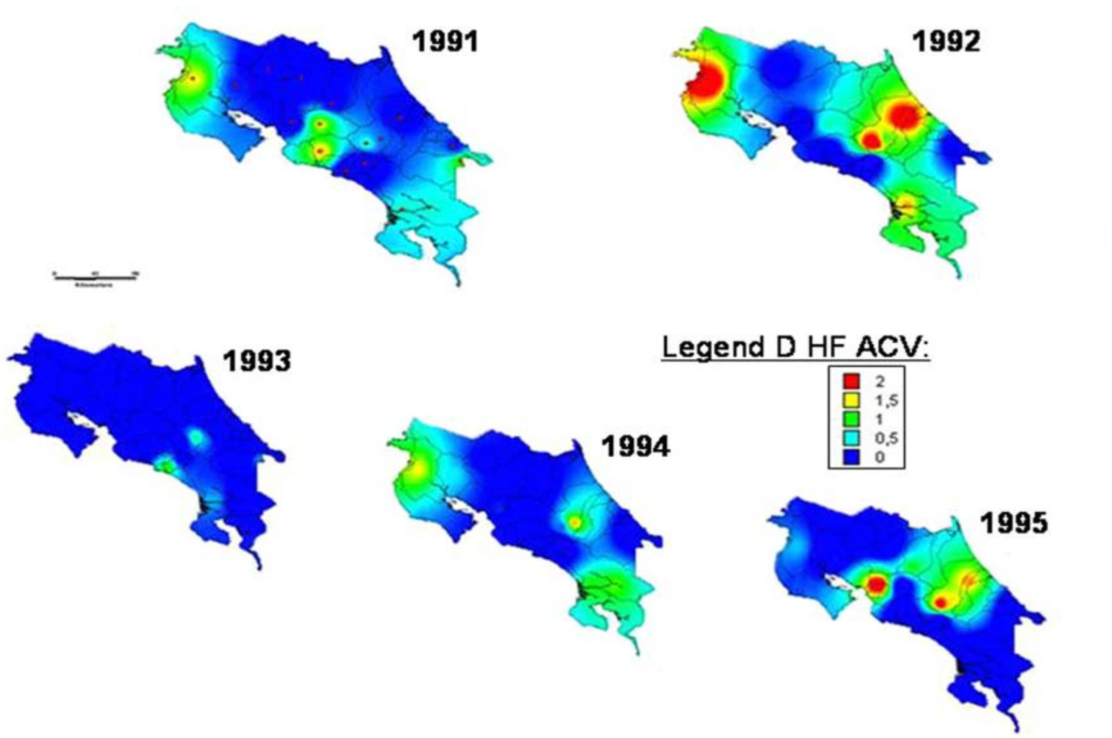


Fig. 4.10 ACV high flow seasonal anomaly index (D) over a drought sequence (1991-1995)

The high flow season in 1991 of Figure 4.10 is already characterised by a severe drought in the North Pacific region, an abnormally severe drought at the Central Pacific and by a slightly severe drought at the South Pacific. This situation affects the 1992 low flow season drought, which causes a prolongation into an excessively severe drought situation during this year’s high flow season. The dry season of 1993 is a year of diversion, except for the North Pacific, while the rainy season of that year shows severe droughts at the Caribbean and the Central Pacific.

This leads to the worst drought situation of that sequence during low flow season of 1994. High flow season shows a slight decrease on the severity scale; while 1995, the situation during dry season can be described as almost normal. 1995 high flow season is characterised by severe droughts at the central Caribbean.

4.2.4 Drought risk

Referring to risk in hydrology understands a multitude of concepts and interpretations. Generally, accepted definitions, such as the international glossary of hydrology (UNESCO/WMO, 2003) understand of risk the potential realisation of unwanted consequences of an event. The definition of risk used in this study according to Tallaksen & van Lanen (2004) is equal to the probability of non-exceedance of a certain maximum level (partial maximum series of drought indices, PDS) within the given period of record using historical streamflow data. No guarantee of stability for the future can be given, because hydrological data are to be assumed of a non-stationary character.

The fundamental concept of *population* is used to calculate the probability of non-exceedance in extreme value statistics, which refers to a set of elements with measurable properties like e.g. the mean value, standard deviation etc. These properties are estimated by the properties of a sample (in our case the available period of record) taken from the population assuming the sample as representative and stationary. The sample values represent real values (x), while values of the unknown population are expressed as random variables (X).

The probability, that the random value X is less than or equal to x, which in other words is the non-exceedance probability for x, is determined by the cumulative distribution function (cdf). Its derivative, the probability density function (pdf) describes the relative likelihood that the continuous random variable X takes on different values. Percentiles of a distribution include cumulative probability p, which has an exceedance probability of 1-p and commonly is expressed as the *return period* T.

T (exceedance probability) is defined as:

$$T = \frac{1}{1-p} \tag{4.2}$$

, where T is the mean time interval between occurrences of an event X>x.

For T (non- exceedance probability) corresponds:

$$T = \frac{1}{p} \tag{4.3}$$

, where T is the recurrence interval between occurrence of an event X≤x.

As mentioned above the definition of risk used in this study is defined according to Tallaksen & van Lanen (2004) as follows:

Probability Pr = {at least one occurrence

of a T- year event in N years} = $$1-\left[1-\frac{1}{T}\right]^{N}$$ **(4.4)**

Following equation **(4.4)**, the probability that a 40 - year event (p = 0,025) in any of the next forty years occurs can be calculated as: $1 - 0{,}975^{40} = 0{,}637$ (risk: 63,7 %). If the risk for any T-year event is calculated, it can be noticed that on average a T-year event occurs once in a T-year period. This means that a 10, 20, 40 or 100 T-year event occurs at least once respectively in that period.

The methodology presented by Zelenhasic & Salvai (1987) for describing and analysing the stochastic process of streamflow droughts was adapted for the program NIZOWKA to estimate drought characteristics. Several frequency studies in different river regimes were brought out to study the most suitable distribution for PDS of deficit characteristics (Madsen & Rosbjerg, 1998; Meigh et al., 2002; Tate et al., 2000; Kjeldsen et al., 2000). The program derives the cumulative distribution function (cdf) of the largest event within one year or season from a partial duration series (PDS) of drought events. PDS of drought events below a defined threshold are automatically selected from the daily time series. The PDS model includes two stochastically components to analyse drought duration (occurrence) and deficit volume (magnitude).

Furthermore, the program allows choosing between several probability distributions for the PDS of AMD and AMV, which are:

- Pearson Type 3 Distribution
- Log-Normal Distribution
- Johnson Distribution
- Gumbel Distribution
- Generalised Pareto Distribution

The goodness-of-fit of the distributions is evaluated by the chi-squared test statistics and additionally the Akaike Criteria is used to discriminate between the different distributions (Akaike, 1974). The literature has to be consulted for further information on this topic.

The distribution that fitted best drought duration and deficit volume was the *Poisson distribution* for the number of droughts and the *Log-Normal* along with the *Pearson distribution* for duration. The *Poisson distribution* was chosen for the number of events and the *Generalised Pareto distribution* for estimating magnitudes of the deficit volume extreme statistics. Figure (Fig. 4.11) demonstrates such a best fit Pearson distribution example for drought duration as displayed by the NIZOWKA program.

Zero flow years (first red dots of low non-exceedance probabilities) affect the adjustment of the distribution function to the PDS, as it can be seen in Figure 4.11. Nevertheless, the observed maximum value is satisfactorily modelled and covers more than 95 % of the non-exceedance probability, which is identical to a return period of 20 years.

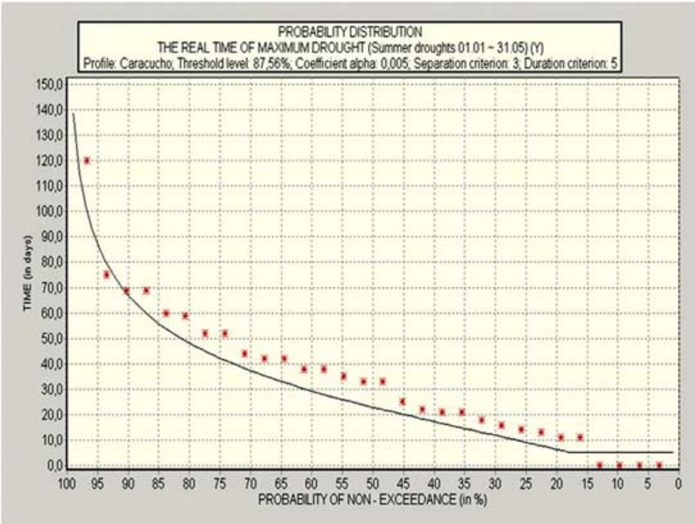


Fig. 4.11 Best fit Pearson distribution for low flow seasonal drought duration PDS

The distribution contains an exponential character to fit best the highest PDS values, which makes it difficult to use an extrapolation over a large period of unobserved data, e.g. for a 100 year return period (99 % probability of non-exceedance). This was the reason to account for the use of a maximum return period of 40 years in interpretation.

The calculated return periods for each gauging station and drought index, which determine drought risk according to the definition above, are regionaised across the study area to gain a general spatial picture of the stations, which can be presumed to run more risk being affected by severe droughts.

The following figure (Fig. 4.12) shows the spatial 10, 20 and 40 years return periods for the low flow season (LF) Q_{70} AMV's (right panel) and the LF Q_{70} AMD's (right panel). The legend of the maximum deficit volume series given in seconds (s) due to standardisation by mean flow.

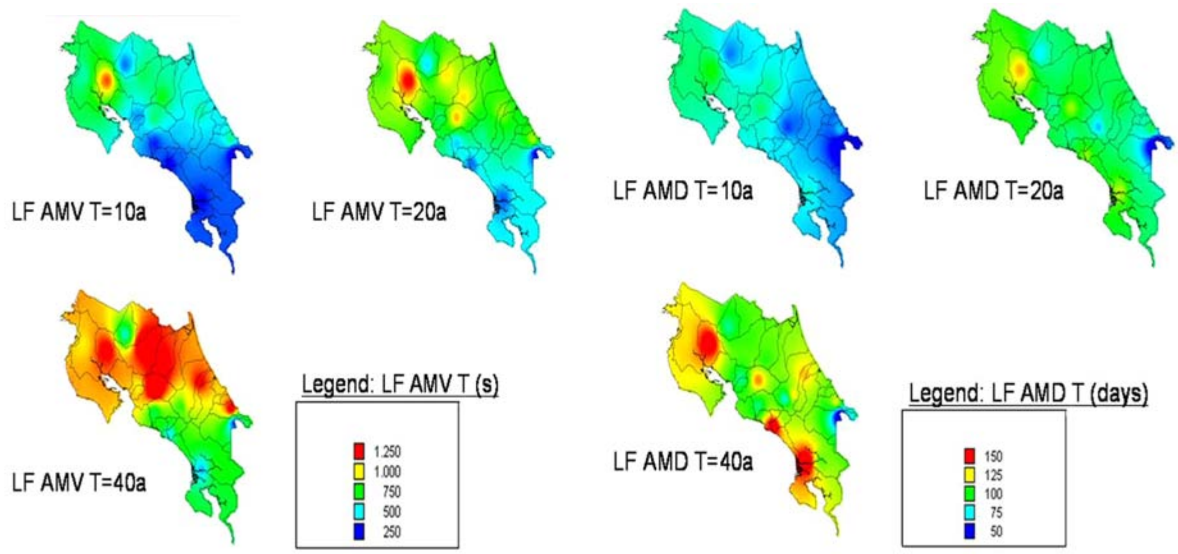


Fig. 4.12 Estimated 10, 20, 40 and 100 years return periods (T) for seasonal (LF) AMV's (left panel) in 1000s and LF AMD's (right panel) in days

The Pacific region is considered according to Figure 4.12 to be of greater risk for drought than the Caribbean displayed by maximum duration indices (right panel), while the deficit volume characteristics (left panel) draw a clear north–south division. What undoubtedly coincides between the two indices is the high drought risk for the North Pacific and parts of the Northern Zone bordering the Caribbean.

Care has to be taken by comparing estimated AMD with AMV spatial patterns, because of their different scale properties. The AMD regional drought risk for 10 years return period-estimates shows the North Pacific, parts of the Northern Zone, the Central Pacific, the Central Valley and the South Pacific as the most affected areas. Obviously, the spatial pattern of high risk, medium risk and low drought risk regions maintain their division into the intensification of risk level. A higher drought risk level for a maximum drought of displayed quantity, which occurs at least once in a period of twenty years (T = 20 years) provokes the development of high risk drought centres and low risk centres, while the whole country is covered by a medium risk level. These centres are located in their original division of high and low drought risk like the Pacific–Caribbean for the AMD (right panel-Fig. 4.12) and the north–south for the AMV (left panel-Fig. 4.12).

Four stations (western Northern Zone, northern Central Pacific, upper and south of the Caribbean) resist a high drought risk of a 40 years return period for the low flow seasonal AMD and AMV, while the rest of the regions show at least a medium drought risk level or a centred high risk level (see left panel of Fig. 4.12). The Caribbean generally is considered a very humid region throughout the year and changes to a drought centre for high drought risk levels, which coincides with the eastern part of the Northern Zone (experienced drought impact of the 1997/98 El Niño).

The risk of a drought lasting over 150 days is evident for the North, Central and South Pacific. The Southern region normally is not considered a very dry area of that magnitude. The latter result compared to the AMV estimation is very surprising, because a clear north–south division shows a complete contrary picture in Figure 4.12. There the South Pacific is displayed experiencing a forty year return period maximum deficit volume of relatively low risk.

In that region a drought of long duration may occur, which means that the daily streamflow falls below a defined threshold level (in that case the low flow seasonal Q_{70} threshold) over the period of drought duration. However, about the quantity of deficit volume below the threshold, the maximum duration index does not provide any information. In fact, the deficit volume index might show a very low quantity of water deficit below the threshold over drought duration time. This result reveals the necessity of the derivation of more than one drought index to provide plausible interpretation by comparing different indices and reflects the temporal behaviour of drought in terms of varying duration and deficit volume according to seasonality.

As a conclusion on the differences between the estimated drought indices can be said, that in the north of Costa Rica from the Pacific to the Caribbean Vertient a drought experience of a high risk level is more probable than in the south, because different indices agree on that topic. Another interesting fact should be pointed at by comparing drought risks from the interseasonal point of view in order to compare low and high flow season at different return periods (T = 10, 20 and 40 years).

Costa Rica reveals two types of streamflow drought, as earlier mentioned above, in terms of minor droughts clustering during wet season and major droughts span dry season.

Is there a distinction in regional drought risk and when, can differences be determined in terms of quantity and spatial distribution?

Figure 4.13 shows estimated AMV's for different return periods (10, 20 and 40 years) during high flow season (HF). Obviously, the low flow seasonal north-south spatial order does not play an important role for high flow seasonal drought risk. It can be said that the estimated deficit volumes for HF excessively exceed the LF counterpart volumes with two contrary exceptions at the North Pacific (see Tab. 4.7), where the LF volumes are higher than the HF values. Keeping in mind that minor droughts of short duration tend to cluster during high flow season, the excessive flow deficit volumes derived by the same Q_{70} seasonal threshold as for low flow season point out the importance for later drought development.

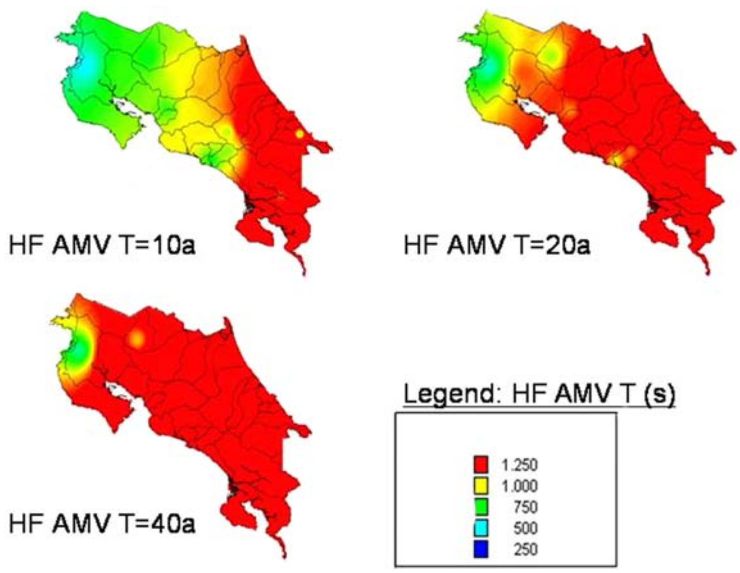


Fig. 4.13 Regionalised estimated high flow season (HF) AMV's for T-10, 20 and 40 years

Higher seasonal discharge and a resulting higher seasonal threshold can produce higher deficits during a drought event. This explanation for the difference in magnitude of wet seasonal deficits might seem to be simple, but compared to temporal drought characteristics surprisingly. The season of the highest precipitation rates can be considered as recharge season due to very consistent in frequency rainfall patterns (see Chapter 2.3.1). If little variation in precipitation frequency occurs, which is likely probable e.g. during active El Niño events (Ramirez, 2004, personal conversation), recharge will be easily disturbed and can be considered to strongly influence low flow seasonal drought behaviour.

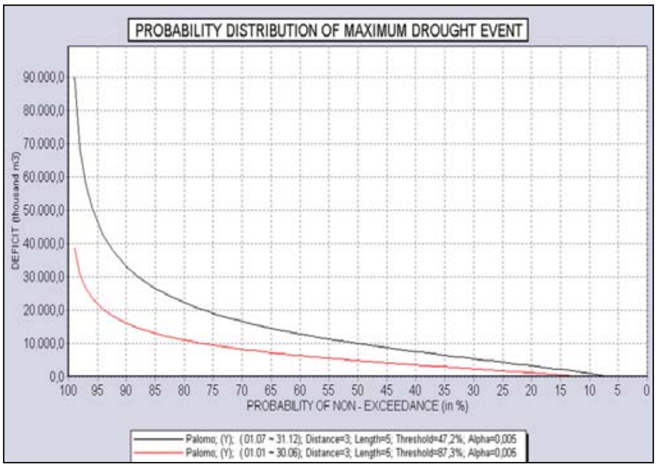


Fig. 4.14 Comparison of HF (black graph) and LF (red graph) seasonal probability distributions for PDS of station „Palomo“over the period 1973-2003

Figure 4.14 shows the difference in magnitude (1000 m^3 non-standardised) of deficit volumes between the high (HF) and low (LF) flow seasonal probability distribution of maximum drought events for station “Palomo”.

The table (Tab. 4.7) presented below shows the best fit estimated seasonal (low, LF and high flow season, HF) deficit volumes in thousand seconds for the return periods T = 10, 20, 40 and 100 years, which is according to equation **(4.4)** referred to as non-exceedance probability p = 0,9; 0,95; 0,975 and 0,99 occurring once in a T-year period. The Poisson distribution was found to fit best the number of droughts for both indices, the AMD and the AMV, the Pearson distribution for duration and the Generalised Pareto distribution for deficit volume.

The table also gives the mean value and standard deviation to compare the quality of estimations. The deviations from the mean value for the ten and twenty years return periods show little uncertainties, which means the estimators are well explained and the probability of the non-exceedance level is completely covered by the observed data.

The forty years return period is already characterised by a higher level of unexplained estimators, while the one hundred years return period in most of the cases extrapolates far beyond the observed range. According to that reason the T = 100 years estimation was not used for interpretation of the spatial drought risk results.

Minimum (blue) and maximum (red) values are colour-coded to better display the extremes. Obviously, station Bratsi located in the Caribbean accounts for the most extreme interseasonal behaviour in terms of low and high flow seasonal drought risk (Tab. 4.7).

Tab. 4.7 Return period (T) statistics for seasonal (LF and HF) AMV indices (max. = red, min. = blue) calculated from the period 1973-2003

		LF AMV				HF AMV			
climatic region	**station**	**T=10**	**T=20**	**T=40**	**T=100**	**T=10**	**T=20**	**T=40**	**T=100**
Northern Zone	GUATUSO	367	468	567	697	737	901	1063	1274
Northern Zone	TERRÓN COL.	662	1027	1502	2342	1005	1371	1804	2503
Northern Zone	CARIBLANCO	742	1039	1390	1952	1074	1381	1717	2209
North Pacific	GUARDIA	590	805	1020	1305	506	575	614	643
North Pacific	RANCHO REY	1180	1289	1324	1338	808	1176	1642	2459
Central Valley	GUAPINOL	396	651	1004	1669	806	1120	1483	2052
Central Valley	TACARES	643	1081	1690	2837	1017	1420	1862	2524
Central Pacific	EL REY	278	448	678	1096	1020	1505	2103	3120
Central Pacific	LONDRES	232	353	512	802	758	1020	1295	1686
Central Pacific	PROVIDENCIA	342	543	809	1283	885	1134	1371	1679
South Pacific	PALMAR	250	340	440	593	1349	1831	2372	3196
South Pacific	CARACUCHO	336	525	775	1220	1201	1689	2274	3237
Caribbean	PALOMO	452	613	780	1061	932	1303	1760	2535
Caribbean	ORIENTE	469	709	1017	1553	1391	2041	2908	4520
Caribbean	DOS MONTANAS	583	888	1280	1964	1419	2073	2943	4560
Caribbean	PANDORA	615	922	1313	1986	906	1214	1574	2147
Caribbean	BRATSI	146	222	314	460	5047	5302	5423	5497
µ:		487	701	966	1421	1227	1592	2012	2697
S:		241	294	390	626	984	1002	1032	1207

4.2.5 Conclusion on spatial drought patterns

Chapter 4.2 presents different applications to gain knowledge of spatial drought patterns across Costa Rica. At first, the maximum events from different drought indices like AMD, AMV were selected and arranged according to their climatic regions. It can be said, that the years of maximum events occurring coincide with the dry years evaluated by the overall indices. Furthermore, the Table 4.5 shows the 70's and early 80's as Caribbean drought years, while the late 80's and 90's are characterised by streamflow droughts at the Pacific Coast. The majority of the streamflow stations ordered by their physiographical division e.g. the North and Central Pacific region show the extreme events of their records in the same year or on two consecutive dry periods. This fact proves reliability on the climatic division for streamflow drought characteristics and drought as a regional hydrological phenomenon.

The most affected regions by extreme drought events can be outlined by a variability index, which reflects drought susceptibility. The higher the variability, the more afflicted by extreme events are catchments. The AMD and AMV indices show the same spatial picture [r (AMD/AMV) ~ 0,8]. The most affected regions are undoubtedly the North Pacific, the Central Pacific and parts of the Caribbean. The seasonal division, however, presents differences in the magnitude of variability.

There, the high flow seasonal values for the most affected stations are higher than its low flow seasonal counterpart, which means a stronger affliction to extreme events during rainy season. In other words, climate variability during wet season might lead to more severe events than during dry season, because in the drought afflicted regions (e.g. the North Pacific region) water deficiency during dry season is experienced as a natural climatic phenomenon.

To better separate natural water deficiency from severe drought, anomaly indices (D) were developed to investigate seasonal drought behaviour. These indices can be regionalised to obtain spatial drought maps. First, the anomaly index was scaled by different severity levels to easily detect regions threatened by drought. Second, drought maps for different seasonal anomalies (LF, HF AMV and AMD) were generated characterising years of drought sequences (1991-1995) revealed by the overall indices. The sequence from 1991 to 1995 shows a certain drought movement across different physiographical regions. Developing in the west and varying in magnitude streamflow droughts make their way to the east and further south. This regional development and extension of streamflow droughts can reach areas, which are normally not considered as drought-proned.

The last study on that topic defines estimated return periods for annual maximum drought indices like duration and deficit volume as drought risk and regionalises a 10, 20 and 40 years return period (T) of non-exceedance probability for every station. Summarised can be said, that the north of Costa Rica (includes one station as exception) runs more risk to experience drought events of the estimated magnitude during low flow season. All stations, except the North Pacific, is assumed to be of high risk to experience high flow seasonal droughts, which points at wet season as principal influence on later dry seasonal drought development.

4.3 Trend analysis

4.3.1 Origin and analysis of trends in drought series

This chapter demonstrates an approach to detect trends in drought series. Trends in historic streamflow drought series might originate from anthropogenic influences, such as river regulation and irrigation. According to IPCC (2001), trends also can be caused by climate change, in particular a change in precipitation and evaporation would cause a change in hydrological drought. Scientists generally agree that the hydrological cycle will intensify and hydrological extremes, such as floods and droughts will become more common due to the projected global temperature increase (Watson et al., 1998). It must be considered that trend analysis is exclusively bound to the availability of the length of time series in order that a trend found might just be part of a natural fluctuation.

Constant non-seasonal annual maximum drought indices as well as the number of droughts within a year can be related to the previously mentioned causes. A trend test realised with these indices is assumed to answer the question if streamflow drought in Costa Rica has become more frequent (in terms of the number of drought events each year, ND) and severe (in terms of duration, AMD, or deficit volumes, AMV). Hisdal et al. (2001) proposed the non-parametric Mann-Kendall trend test (MK) due to skewness of hydrological data.

Mann (1945) and Kendall (1975) first initiated detecting trends in time series by the proposal of a robust, simple and non-parametric rank-based test for correlation of two variables, which in this case are time and drought series. The univariate *MK* statistic for a time series $\{Z_k, k = 1, 2, \ldots, n\}$ of data is defined as:

$$T = \sum_{j<i} \mathrm{sgn}(Z_i - Z_j) \qquad \textbf{(4.5)}$$

, where

$$\mathrm{sgn}(x) = \begin{cases} 1, & if\ x > 0 \\ 0, & if\ x = 0 \\ -1, & if\ x < 0 \end{cases}$$

If no ties between the observations are present and no trend is present in the time series, the test statistic is asymptotically normal distributed with

$$E\,(T) = 0 \quad \text{and} \quad Var\,(T) = n(n-1)\,(2n+5)\,/\,18 \qquad \textbf{(4.6)}$$

E (T) …expectation of the MK test statistic T (-)
Var (T) …variance of the MK test statistic T (-)

The hypothesis of an upward or downward trend cannot be rejected at a significance level α if $|T| > u_1\text{-}\alpha/2$, where $u_1\text{-}\alpha/2$ is the 1-α/2 quantile of the standard normal distribution. The test was performed on three drought parameters (AMD, AMV and ND) derived with a constant non-seasonal threshold of Q_{90} (Chapter 3.2.2), applying a two sided test with a five percent ($\alpha = 0.05$) level of significance. The results were assessed in summary statistics on the significant trends and mapping of the spatial variability of the trends.

4.3.2 Trends in Costa Rican drought series

For most stations, the test results for the distinct drought parameters AMD and AMV are similar; the number of droughts partly show a contradicting picture. For most periods, the number of negative trends in both annual maximum series indicating a decrease in drought severity or frequency exactly equals the number of positive trend test results. Although, just two significant trends (positive) in Costa Rican drought series were found for the ND and AMV of two distinct stations located in the same climatic region (Northern Zone), clear regional patterns in trends were found.

Figure 4.15 shows the trend statistics for the Mann-Kendall test results on AMV for the available periods of the station's records (Tab. 4.8). The stations exhibiting a significant trend seem to cluster in the same climatic region and the neighbour stations tend to show similar trend characteristics.
The most apparent Costa Rican region, where drought severity significantly increased is the western part of the Northern Zone.

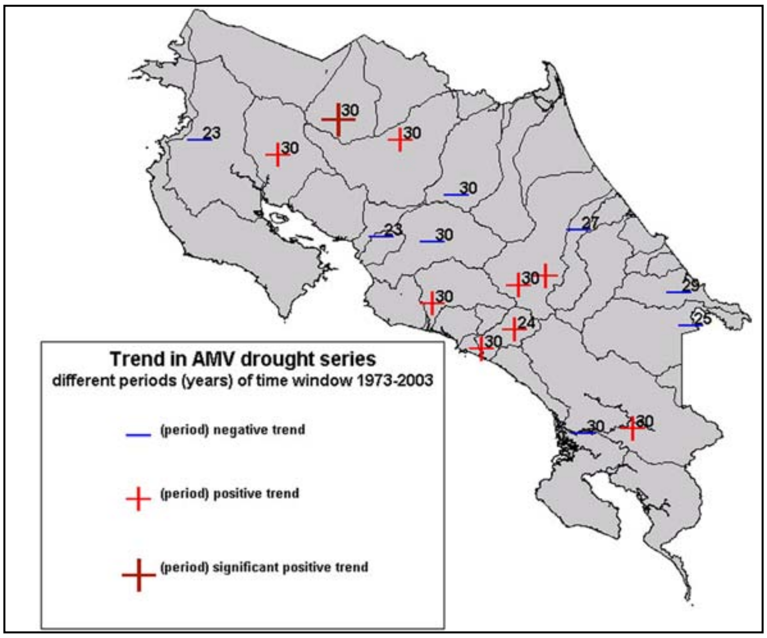


Fig. 4.15 Trends in AMV drought series of all stations for the period 1973-2003

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 tend to increasing drought severity.
The frequency of droughts, in terms of the annual number of drought events (ND), shows a slightly different pattern (see Figure 4.16 under Appendix). The North Pacific region and the Caribbean, both regions indicate a trend towards decreased frequency, while the Central Pacific region and the Northern Zone maintain their tendency even in terms of frequency towards a positive trend. The Central Valley and the South Pacific region show an indifferent pattern for drought frequency.

The mountainous stations of the Caribbean additionally show a trend towards fewer numbers of drought events per year combined with more severe droughts. This principally might be explained by physical characteristics (most important: storage capacity) of these catchments.

Table 4.8 gives a detailed overview of obtained trend statistics from the Mann-Kendall test on trends in all available streamflow drought series for different mentioned periods of the commonly used time window from 1973 to 2003.

Tab. 4.8 Summary statistics on the significance of trends per station record (period: 1973-2003) and climatic region

climatic region	station	record (a)	AMD	AMV	ND
Northern Zone	Guatuso	30	+	+	++
Northern Zone	Terrón Col.	30	-	++	+
Northern Zone	Cariblanco	30	-	-	-
North Pacific	Guardia	23	-	-	-
North Pacific	Rancho Rey	30	+	-	+
Central Valley	Guapinol	23	0	-	-
Central Valley	Tacares	30	-	+	-
Central Pacific	El Rey	30	+	+	+
Central Pacific	Londres	30	+	+	+
Central Pacific	Providencia	24	+	-	+
South Pacific	Palmar	30	-	-	-
South Pacific	Caracucho	30	+	+	+
Caribbean	Palomo	30	+	-	+
Caribbean	Oriente	30	+	-	+
Caribbean	Dos Mont.	27	-	-	-
Caribbean	Pandora	29	-	-	-
Caribbean	Bratsi	25	-	-	-

Legend of symbols:
++ …significant positive trend
+ …positive trend
0 …no trend
- …negative trend
-- …significant negative trend

The trend analysis for streamflow drought revealed no clear indication that streamflow drought conditions in Costa Rica have generally become more severe or frequent in the time periods studied. However, for the common periods, clear regional patterns were found. Although for Costa Rica as a whole trends favouring towards decreasing or increasing drought severity were not obtained, drought frequency has actually decreased in terms of fewer drought events occur. Regions like the Northern Zone and the Central Pacific clearly tend to more severe droughts, while the Central Valley exhibits less severe droughts. The mountainous region of the Caribbean, one station at the North Pacific region and one station at the Central Pacific show less drought events occurring combined with more severe droughts. This might be explained by physical characteristics such as natural storage capacities of the catchments.

Hisdal et al. (2001) discuss evident causes for changed drought severity and frequency across Europe, which can be related to changes in precipitation patterns and indirect artificial influences in the catchments. Such regional studies do not yet exist for Costa Rica, but causes in trends of drought series in Costa Rica can be seen as familiar with causes in trends in Europe. In fact, Hisdal et al. and Stahl (2001) reveal in their trend analysis across European drought series generally comparable results for the Mann-Kendall AMV test statistic with MK AMV results for Costa Rica.

Trends are strongly influenced by the records selected for analysis and by the drought parameters. The importance of the temporal aspect could not be demonstrated due to the lack of longer available drought series, but is evidently discussed in several studies (Hirsch et al., 1982; Hisdal et al., 2001 and Stahl, 2001). A trend in drought series towards an increased or decreased drought severity or frequency based on a relatively short period of record might turn out to be part of a long-term, natural climatic fluctuation. Hence, trends in drought series can not be seen as evidence for anthropogenic-induced climate change.

4.3 Summary

This section is supposed to summarise obtained results and knowledge on drought behaviour of Costa Rican streamflows. Results under discussion and required suggestions for further studies on that topic are given. The clear Costa Rican temporal and spatial drought behaviour proved the applicability, adaptability and adequacy of the threshold method to investigate Neotropical streamflow droughts. The influence of the time period on the threshold level was not possible to evaluate, because longer registers than 30 years are not available. According to Stahl (2001), drought indices vary considerably for small changes of the threshold level and the period of record used for a study should be chosen with care. This particularly must be considered for defining drought risk and trends in drought series with a common period of maximal thirty years.

Streamflow data represents point data, which integrate streamflow characteristics from the catchment above. Out of a total of 49 gauging stations, 17 could be used for this study with an adequate length of record, common time window and with as less as possible known human influence fulfilling statistical requirements. A proper visualisation of spatial drought patterns like drought movement over a sequence of dry years on a national scale requires compromises.

Regionalisation of drought parameters across ungauged catchments to fill “white spaces” by highly uncertain, interpolated estimations must be degraded to merely visual objectives or substituted by displaying point data. Both visualisation methods were chosen to display spatial drought patterns.

However, considering these facts on uncertainty of computed interpolations, maps can be considered an adequate tool to initiate interpretations and visualise regional drought patterns (Odziomek, 2000). Great opportunities for the future exist in evaluating various methods for an improvement and better understanding of regional drought behaviour by regionalisation of drought parameters at the ungauged site.

The seasonally constant threshold approach presents a modification for regional neotropical regime characteristics and allows studying probable causes of streamflow drought manifested in seasonal interactivity.

The hypothesis presented in this work that high flow season deficits likely lead to streamflow drought situations in the following low flow season could be demonstrated by plotted seasonally anomaly indices (high versus low flow season) and seasonal drought risk comparison. The majority of explored historical drought events follow this scheme, but a strong deficit anomaly during wet season does not necessarily cause a low flow season drought. It could be discovered by examining the occurrence of drought durations longer than twenty days during high flow season that the main recharge period at the Pacific Vertient is from August until November. Drought events appearing during early wet season (in some regions part of the natural precipitation and flow regime, called “little summer” during June, July) are considered to have less effects on dry seasonal drought development and are presumed to be a prolongation of dry season drought events.

This is the result of physiographical catchment’s- and climatic characteristics. The first rainfalls e.g. at the North Pacific and Central Pacific region during May and June (wet season starts depending on the region’s climatic characteristics) are of high intensity and variability hitting soil properties exhausted by a long period of dryness. This condition predefines a fast torrential discharge leaving little water for recharging groundwater reservoirs.

This effect might support climatic variability causing ongoing wet season deficiencies, which might affect the drought situation for dry season. In this order, it can be spoken of a chain of causes, one exceeding the next by resuming its effects. This explanation also does not seem to satisfactorily fit for all investigated cases leaving space for hypothesis to prove. One of those might be to derive daily anomaly rainfall indices as a reference for climatic variability, which can be directly compared to streamflow anomalies in order to obtain further knowledge of streamflow behaviour affected through the hydrological cycle.

Another hypothesis is that of present multi-year drought persistence caused by atmospheric circulation patterns like ENSO, which is according to Ramirez (personal conversation, 2005) assumed to play an important role on drought development in the region.

The cumulated indices were used to reveal the real drought effect on regions experiencing drought as a natural climatic phenomenon during dry season (e.g. the North Pacific region). These standardised anomaly indices turned out to be most useful for comparing different indices with different seasonality affecting catchments of different physiographical characteristics. Moreover, the derived anomalies are considered to be independent from regional climate characteristics and seem to be an adequate tool to detect relations between streamflow drought and atmospheric circulation (ENSO).

The spatial drought behaviour study revealed an extremely variable spatial extension of droughts in the region in the order that neighbour catchments show absolutely contrary streamflow drought characteristics at the same time. This variability makes the dependence on the periods of streamflow records (1973-2003) utilised clear and almost imposes a constant monitoring system, especially for drought forecasting.

What clearly can be seen in the spatial study is a regional pattern of more and less affected regions compared to each other on the hand of different drought indices. In terms of succeeding maximum drought events, a general geographic division into the Pacific and Caribbean Vertient is visible in the way that the most severe droughts took place at the Pacific region.

Talking about estimated drought risk in terms of duration and deficit volume, a modification of regional patterns for different results of different drought indices must be explained. The risk for different return periods (10, 20 and 40 years) of estimated AMV's reveals a clear north–south division, while the respectively, estimated AMD's show various drought risk centres across the country. Coinciding for both estimated indices defining drought risk for different return periods, the region of the North of Costa Rica (includes the North Pacific region, the Northern Zone and the north of the Caribbean) is running more risk experiencing drought than the other parts of the country. This frequency analysis applied on the basis of the available time series contains uncertainties, which could be decreased e.g. by increasing the number of events resulting in a larger Partial Duration Series (>PDS).

The comparability with other spatial studies could be significantly increased by developing this method for a PDS of Anomaly Indices in order to define the real drought risk excluding the naturally experienced streamflow deficits. However, this method shows reliable results in this work and offers many opportunities for further regional studies.

Such study is the spatial mapping of anomaly indices over a sequence of dry years (1991-1995), which revealed a certain movement of streamflow drought across distinct regions. The first year of the sequence shows a severe drought in the far Northeast wandering from year to year farther west by extending its region of influence among the Northern Zone farther to the Caribbean and by maintaining its origin.

Another sequence tested for the dry years 1985-1989, discovered by the overall calculation shows an identical, but weaker in severity, drought movement across the same regions. This proves for the period of record investigated, that during a certain persistent drought situation (sequence) drought severity develops by spatial extension (drought movement).

In the case of the Northern Zone and in particular for the Caribbean the last two presented results are quite astonishing. Although these regions experience more than 4000 mm rainfall throughout the year, far more than the rest of the regions under study, the results clearly determine a threat by drought.

A point of discussion is how drought in these regions compared to others is experienced in the term of severity. The Anomaly Indices reveal a more or lower than normal (mean drought) streamflow drought situation and in that term there is no discrimination made between the different regions.

This is a great advantage when comparability is guaranteed, but in the case of the Caribbean, this must be discussed, because the northeastern region of Costa Rica reportedly did not suffer as much socioeconomic losses as e.g. the North Pacific region. Reasons might be searched for in different influences of climatic circulations, which manifest in the seasonality of Caribbean streamflow.

This seasonality is less present than in other regions accompanied by more intensive and variable precipitation patterns. Heavy rainfalls during low flow season are not rare, but not enough to fully decompensate streamflow deficits. Moreover, this climatic variability might help just enough to prevent great socioeconomic damages. To better understand this phenomenon, the anomaly indices should be "calibrated" as mentioned earlier by precipitation anomaly indices, which can be derived in the same manner using thresholds to derive meteorological drought indices. Another approach would be to apply a monthly or daily varying threshold level to detect distinctive streamflow drought behaviour for the Caribbean.

Finally, can be said that different applications reveal comparable results of regional drought behaviour. The North and Central Pacific regions can be undoubtedly seen as the most affected regions by streamflow drought, whether regions like the Northern Zone and parts of the Caribbean that are normally not considered as dry areas due to higher annual precipitations, might be strongly threatened by drought under pursuant climatic conditions.

5 Atmospheric circulation and regional streamflow drought

To study the influence of atmospheric circulation on regional streamflow drought several aspects are investigated;

a) the statistical pre-processing of data in order to adequately realise a correlation analysis including the test on autocorrelation, linearity and normal distribution of the indices applied

b) the cross-correlation analysis is supposed to reveal possible time lags in the effect of atmospheric circulation anomalies on drought

c) the interseasonal relation derived by Pearson correlation coefficients is spatially displayed in order to reveal regional patterns of such interrelations

d) the temporal and spatial results of the correlation analysis for Costa Rica can be compared to European drought characteristics?

5.1 Introduction

The El Niño-phenomenon widely causes effects on Costa Rican climate and it is from the early 80's on, subject of various investigations (Rogers, 1988; Ramirez, 1992; Waylen et al., 1994; Alfaro & Cid, 1998 and Alfaro, 1999). As one of the areas first and most directly affected by the El Niño-Pacific Ocean warming (Glantz et al., 1991), Costa Rica is a site of climate research on the evolution of this climate phenomenon. The socioeconomic impacts developed an intense public discourse in the media, which led to several early warning approaches. Today the role of El Niño in global climate variability and its impact on climatic change have become key questions for understanding current and future climate.

Nevertheless, it took some time (since the 90's) to establish the theory, that Costa Rican droughts are connected to atmospheric circulations like El Niño- Southern Oscillation (ENSO). The climate-related anomalies and impacts of the severe 1982/83 El Niño event were not recognised as a part of this climatic phenomenon at that time, even though droughts were described and documented as climate variability. Climate variability was considered to be limited to the region of Peru and Ecuador. Not until the late 80's, droughts and other climate-related hydrological extremes were described as a part of the El Niño-phenomenon. First published was a study on that topic from Patricia Ramirez (1992), who investigated historical meteorological data for agricultural benefit. In 1996, she identified in a personal conversation with Michael Glantz (1996), who actually established a direct connection between climate-related anomalies and ENSO, the coincidence of periodic droughts in the country with the occurrence of El Niño years.

5.2 El Niño-Southern Oscillation (ENSO)

El Niño can be briefly defined as the anomalous, periodic appearance of warm sea surface temperatures in the central and eastern equatorial Pacific Ocean. *The Southern Oscillation* refers to a seesaw-like atmospheric pressure pattern in the western part of the tropical Pacific. El Niño originally referred to the appearance of warm water off the coast of Peru and Ecuador, where the up welling of deep Cold Ocean water normally occurs. By the 70's, it was realised that these two Pacific basin phenomena interact affecting climate processes around the globe and those basin wide effects are defined as *ENSO*.

ENSO consists of two components:

- The oceanic component oscillating around its warm phase called El Niño and its corresponding cold phase La Niña.
- The atmospheric component is reflected in an atmospheric pressure change between the occidental and oriental-central sector of the tropical Pacific Ocean, numerically described as Southern Oscillation Index (SOI).

Due to the extension of the Pacific Ocean, the scientific community agreed in a regional division of different indices (seen in Figure 5.1 as Niño 1.2, Niño 3, Niño 3.4 and Niño 4). This is important for later analysis, when several oscillation indices are tested for correlation with regional drought.

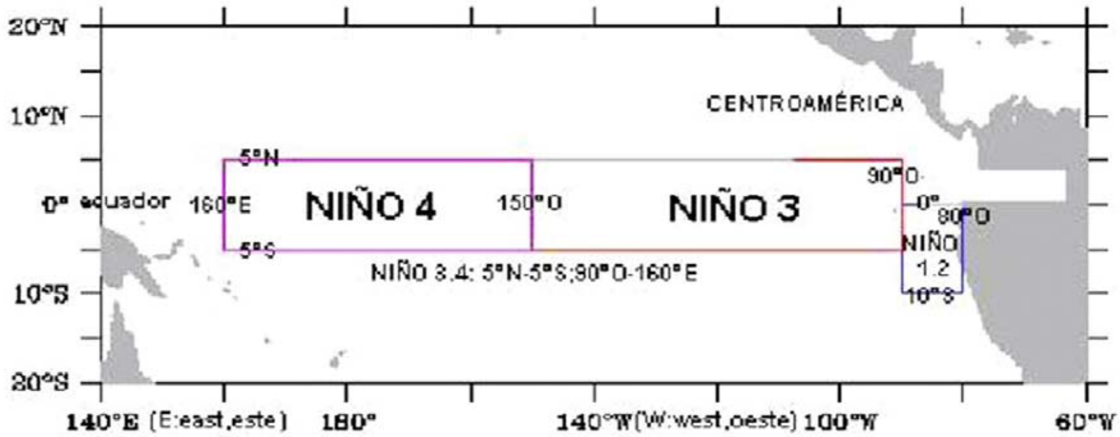


Fig. 5.1 The four Niño regions of the Pacific Ocean, after NOAA (www.elnino.noaa.gov/edu.html)

For a better understanding of the ENSO phenomenon the spatial and temporal distribution of equatorial superficial ocean temperatures and superficial pressure patterns, have to be studied. Figure 5.2 shows three scenarios of the spatial temperature distribution across the equatorial Pacific Ocean. The first scenario demonstrates a La Niña event (cold phase), the next one reflects normal temperature conditions and the third scenario gives the warm phase temperature anomalies (El Niño event).

The intensity of the El Niño phenomenon can be according to NOAA classified after its temperature anomaly, even though various intensity scaling approaches exist:

a) El Niño – *weak or moderate intensity*: **0.3°C** < temperature anomaly < **0.8°C**
b) El Niño – *strong intensity*: **0.8°C** < temperature anomaly < **1.2°C**
c) El Niño – *very strong intensity*: temperature anomaly > **1.2°C**

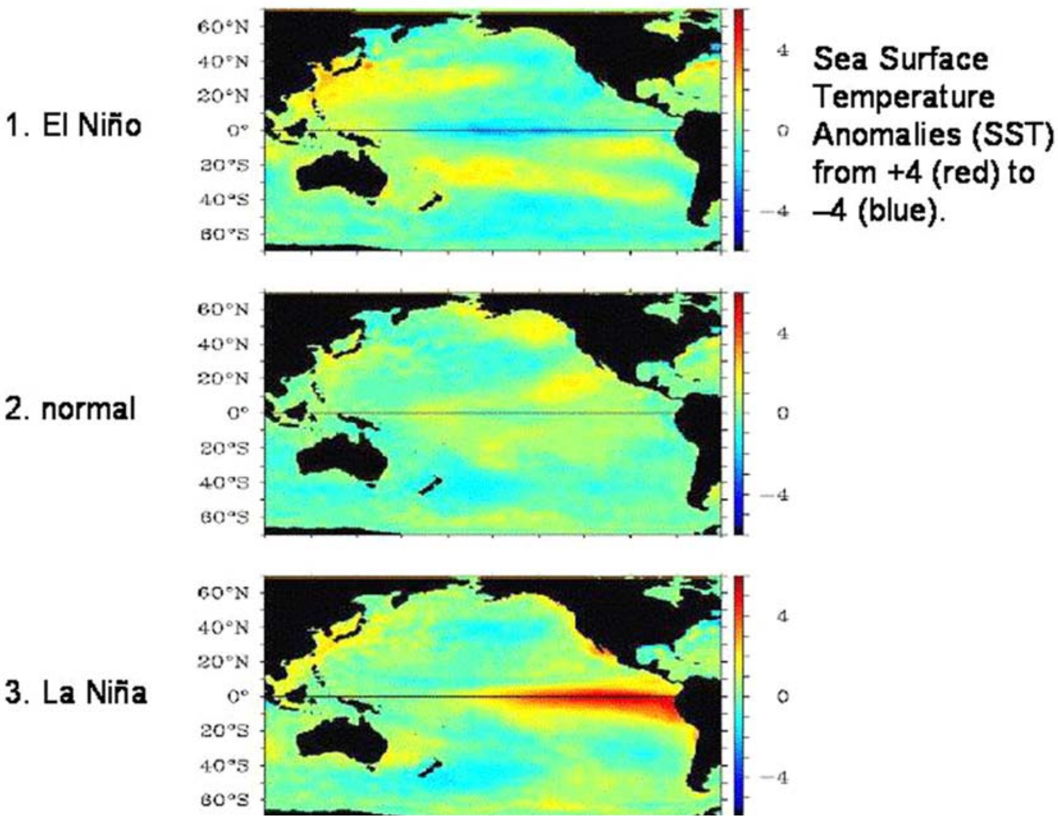


Fig. 5.2 Three spatial temperature scenarios of the equatorial Pacific Ocean modified after (http://www.cpc.ncep.noaa.gov/products/analysis_monitoring/impacts/enso.html)

The equatorial sea surface temperature is measured and translated into regionally classified indices (e.g. SST 3.0) depending on the internationally accepted spatial distribution of the different El Niño regions mentioned above (Fig. 5.1). Negative SST values are to be referred to a cold phase or La Niña event, while positive temperature anomalies reflect a warm phase or El Niño event. This classification turns to the contrary for the SOI, which reflects the surface pressure pattern departures.

It is possible to detect the exact state of an active phase, either El Niño (warm phase) or La Niña (cold phase). These anomaly indices are to be set in relation to the streamflow drought indices to obtain possibly effects on Costa Rican drought behaviour. A direct relation can be e.g. realised by linear regression with a correlation coefficient reflecting the grade of association between two data series.

It might be a good question to ask for the consequences and effects of a sea surface temperature and pressure pattern change at the equatorial Pacific Ocean on Central American climate variability and in particularly for Costa Rica. For that purpose, the Figure 5.3 below shows the link of sea surface temperature on oceanic and continental climate. Characteristics of a warm phase event show positive sea surface temperature deviations due to a deep lying thermocline blocking normally cold water up welling at the coast of Peru and Ecuador. The warming sea surface causes convective rainfalls at the oceanic equator by disturbing the east–west Walker circulation, which leaves Australia and Indonesia without precipitation. As it can be seen in the figure (Fig. 5.3) below, the circulating wind system tends to be of a very weak magnitude and even can overturn its normal direction to blowing from west to east. This has global consequences on land-hydrologic systems causing hydrological variations in many regions at an interseasonal, interannual and even decadal time scale. In Central America, precipitation patterns during wet season months from June to August are characterised drier than normal (Rogers, 1988; Waylen et al., 1994; Ropelewski & Halpert, 1986, 1996; Ramirez, 1997 and IMN Costa Rica, 1998), which is presumed to associate with streamflow patterns in the region (Chiew & McMahon, 2002).

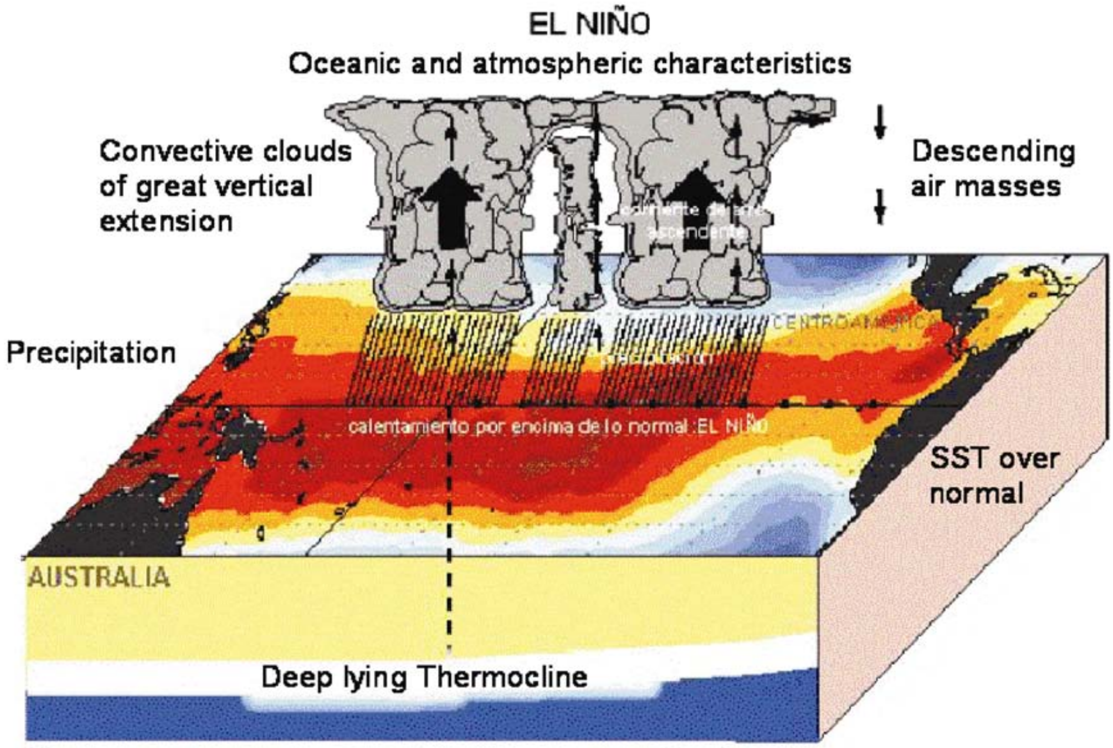


Fig. 5.3 Oceanic and atmospheric El Niño characteristics modified after NOAA

The El Niño counterpart of the Southern Oscillation (La Niña) manifests in lower than normal sea surface temperatures at the equatorial Pacific Ocean. This can be seen (Fig. 5.4) in the superficial state of the equatorial thermocline in the east, while the thermocline in the west lies very deeply.

Precipitations are produced in the equatorial west, in the Australian and Indonesian sector due to the interference of the east–west Walker circulation. Winds circulate very close to the seasurface from the equatorial east to the west. Precipitation patterns across Costa Rica convert to higher than normal intensities during wet season months from June to August (IMN Costa Rica, 1998; Retana, 1999).

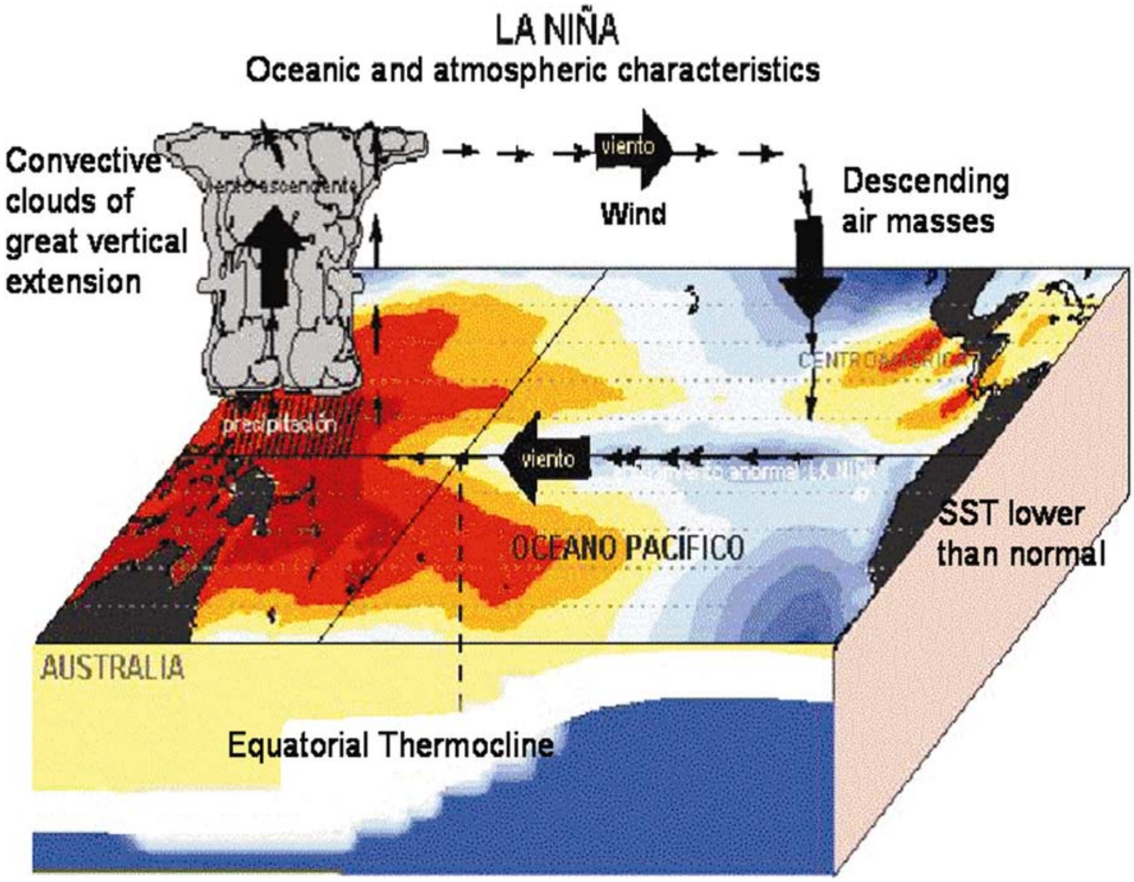


Fig. 5.4 Oceanic and atmospheric La Niña characteristics modified after NOAA

Constant monitoring (service provided by NOAA) of oceanic sea surface temperatures and atmospheric pressure patterns allowed to reconstruct historical El Niño and La Niña events. This even permits the forecast of future events in magnitude, temporal and spatial distribution. Inundations and droughts are reported (IMN, 2000 and Ramirez, 1994) hydrological extremes across Costa Rica, which can be associated to observed ENSO events. Gaining knowledge about such teleconnections, e.g. on how the oceanic-atmospheric circulation system affects the region's climate variability. The possibly strongest ENSO event of the last century in 1997/98 was well documented and can be taken as reference.

The IMN (National Meteorological Institute) bulletin (1999) and CEPAL (Economic Commission for Latin America and the Caribbean) (1999) report a high magnitude El Niño event from May to August 1997 associated with flooding and inundations at the Caribbean causing various human victims and high economic damages.

The North Pacific region and the Northern Zone suffered from a severe drought from January until June of 1998 provoking high damages in the agricultural sector (Tab. 1.1). More intensive rainfalls than normal at the Caribbean and less precipitation than the average at the Pacific Vertient is considered causing a typical impact pattern of El Niño events. Various other extreme climatically induced events and their impacts are reported, such as local tornados, a more active hurricane season, higher fish mortality in rivers and the Pacific Ocean, landslides, avalanches and forest fires.

Even though, drought at the Pacific is a main impact; there were increased water damages on crops like flooding registered (CORECA/MAG, 1997). This seems to contradict the general perception of drought impact, but according to a personal conversation with Patricia Ramirez (2004) precipitation totals during El Niño years do not vary significantly from long-term averages. In fact, rainfall pattern changes and tends to cluster in very short time periods, so that aquifers do not recharge and damages occur due to an intensification of precipitations. This change in precipitation frequency towards few very intensive events and long non-rainfall periods seems to be directly associated to El Niño climate variability of the region.

The 1997/98 ENSO event exceeds in magnitude a similar reported event from the years 1982/83. Both high-magnitude El Niño events occurred characterised by identical spatial and temporal impact patterns as mentioned above. Minor events were recorded for the years 1976/77, 1986/87, 1992/93 and 2002/03 with variable impacts causing relatively “moderate” damages.

Retana (1999) associates typical dry events at the Pacific Vertient with the warm phase of ENSO. Nevertheless, deviations in magnitude of ENSO events and temporal and spatial climate variability must be considered. Retana created in his quantitative ENSO study five scenarios to characterise annual precipitation registers of 37 stations across the country. For every station and scenario the percentage of the occurrence frequency of warm phase events were calculated and expressed in terms of probability of a dry, normal or wet El Niño event. These scenarios give a spatial perception of the annual climate variability across Costa Rica. High percentages (50 - 80 %) for a dry El Niño event and low probabilities (0 - 20 %) for a wet event were obtained at the Pacific Vertient. As mentioned above the reported climatic impacts for the Caribbean region coincide after this study with a high probability (30 - 70 %) for wet events.

Other studies (Ropelewski & Halpert, 1996) attempt to quantify the relationship between precipitation patterns and the Southern Oscillation in order to provide useful information for long-term climatic forecast. Ropelewski & Folland (2000), even give prospects for predicting meteorological drought based on a quantification of climate variability and Alfaro et al. (1998) found the dependence of the initiation of Central American rainy season in Pacific and Atlantic Oscillations.

5.3 Linking circulation pattern occurrence to regional streamflow drought

Reported El Niño experiences and studies on climate variability indicate a certain spatial and temporal hydrological impact pattern. ENSO, an oceanic-atmospheric circulation pattern, has direct effects on the hydrological cycle in the region of Central America and in particularly of Costa Rica. Changes in precipitation frequency and precipitation probabilities are assumed to affect streamflow in order to be able to establish simple linear correlations of Costa Rican streamflow drought anomalies with the ENSO indices (SST, SOI).

Dettinger et al. (2003) combined SOI with streamflow totals in the Americas and found high correlations for Central America. This study uses a global grid of low resolution for the calculations, but proves the existence and highly dependent relationship of ENSO signals and regional streamflows. A strong teleconnection of the hydrological cycle and El Niño reveal Krasovskaia, Gottschalk & Laporte (1999) with the dependence of the frequency and magnitude of extreme floods in Costa Rica on the Southern Oscillation Index. They confirm in the term of streamflow the hypothesis of Ramirez (2004, personal conversation), that ENSO remarkably changes frequency patterns of precipitations among affected regions. The frequency of extreme floods corresponds to an atmospherically pattern, which points to interpret towards a similar relation of the hydrological counterpart (drought).

Webster (1994), Piechota & Dracup (1996), Sun & Furbish (1997), Poveda & Mesa (1997), Cao (2000), Ropelewski & Folland (2000) and Waylen & Poveda (2002) revealed various associations of the El Niño-Southern Oscillation with drought and regional hydrological variations in the Americas. These studies either use the Southern Oscillation Index (SOI) or Sea Surface Temperature departures (SST) to establish computed interactions with either precipitation or streamflow anomalies.
None of these investigations, however, studies teleconnections of ENSO on drought behaviour, neither in Costa Rica nor with an adequate resolution. This work presents temporal and spatial drought characteristics at a national scale to reveal possible spatially varying teleconnection signals. Seasonally derived drought anomaly indices represent a standardised tool free of regional climatic characteristics. Indeed, these comparable indices make a spatial study at a relatively small scale like Costa Rica feasible.

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.). These indices must be averaged according to the identical seasonality as for the anomaly indices to properly become comparable.

Furthermore, according to Dettinger et al. (2003) linear correlations of American flow series with SOI can be used to separate influences of El Niño and La Niña on Western Hemisphere streamflows.

Correlation analysis

It might be of interest to determine seasonal relationships between hydrological (ACV and precipitation anomalies P) and atmospheric (SST) indicators. Moreover, the correlation study is supposed to reveal warm and cold phase impacts on the hydrological cycle, as well as its timing or retention on single hydrological components in terms of precipitation and streamflow. Discharge can be assumed to react with a delay on precipitation impacts due to catchment's characteristics.

As mentioned before recharge deficits during wet season can be considered the primary cause of severe low flow seasonal droughts. According to Retana (1999) and others, a drier than normal wet season (June to September) is supposed to be a major El Niño-effect on Central American climate. These interseasonal, but also interannual effects of ENSO on droughts in Costa Rica are to be proved.
The seasonally standardised anomaly indices are used to produce linear correlation matrices coupled with respectively, seasonal precipitation anomalies for the corresponding climatic region and season and seasonal oscillation indices (SST 3.0, SOI and NAOI). The results are assessed in terms of correlation matrices, graphically plotted correlation matrices and regionally displayed maps of correlations.

A standard tool to measure the strength of a linear relationship between two variables is the Pearson correlation coefficient r, which is computed as follows:

$$r = \frac{\sum_{i=1}^{N}(X_i - \mu)(Y - \mu_i)}{(n-1)S_x S_y} \qquad \textbf{(5.0)}$$

, where S stands for standard deviation (-) and μ respectively for the mean values (-) of data series.

The correlation coefficient of a linear relationship between two variables is always between -1 and +1. The closer the correlation is to +/-1, the closer to a perfect linear relationship. Here is how I tend to interpret correlations of hydrological-atmospheric relationships:

- **-1.0** to **-0.6** strong negative association
- **-0.6** to **-0.2** moderate negative association
- **-0.2** to **+0.2** little or no association
- **+0.2** to **+0.6** moderate positive association
- **+0.6** to **+1.0** strong positive association

The Pearson Product Correlation Coefficient r applied to hydrological and climatic data requires statistical assumptions for proper computation:

a) no or low autocorrelation
b) linearity of data series and
c) approximately normal distributed data.

The seasonally derived anomaly indices (ACV, ENSO indices and P) can be assumed to be of reduced autocorrelation due seasonally averaging (ENSO indices) and the standardisation process in terms of their seasonal long-term average and standard deviation **(Eq. 4.1)**.

a) test on autocorrelation

Figure 5.5 shows an example for the calculated **(Eq. 4.0)** lag-one autocorrelation coefficients r (1) of a seasonally derived sea surface temperature anomaly SST 3.0 (left panel: low flow season, LF), the ACV LF for station Rancho Rey (middle panel) and the low flow season precipitation anomalies of station Nicoya (right panel). The r (1) values lie in between the 95 % confidence bands. Please note that the first lag-one value lies inside the confidence limits.

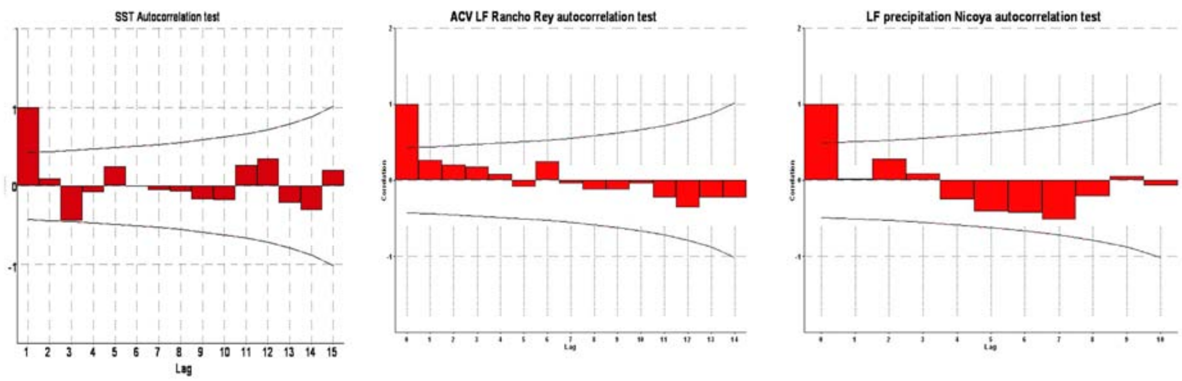


Fig. 5.5 Autocorrelation coefficients r (1) for components of the correlation study:
- SST LF (left panel) for the period 1973-2003
- ACV LF station Rancho Rey (middle panel) for the period 1973-2003
- P LF station Nicoya (right panel) for the period 1973-2003

All implemented indices were tested on autocorrelation and can be assumed to be free of serial correlation with minor exceptions.

b) test on linearity

Moreover, all correlations are calculated for one more distinct definition, which is supposed to provide adequate information in case of non-linearity. Such is the Spearman Rank Order Correlation Coefficient r_s designed to measure correlation of ranked ordinal data:

$$r_s = 1 - \frac{\sigma\left(\sum D^2\right)}{N\left(N^2 - 1\right)} \qquad \textbf{(5.1)}$$

σ … a constant (-)
D … difference between ranks of two variables (-)
N … number of subjects (-)

The following table (Tab. 5.1) shows a correlation matrix example from the Central Pacific climatic region for components of the hydrological cycle (anomaly indices of drought ACV and precipitation P) and atmospheric circulation (e.g. SST).
Please notice, that all correlations are statistically tested on significance and exclusively mentioned for interpretation with an association at a significance level of at least α = 0,1.

Tab. 5.1 Central Pacific region low flow season correlation matrix for Pearson and Spearman coefficients between:
- precipitation *P* anomalies of station Palo Seco for the period 1973-2003
- drought anomalies *ACV* of station Providencia, Londres and El Rey for the period 1973-2003
- atmospheric anomalies *SST* 3.0 for the period 1973-2003

correlation matrix		**Spearman ρ**				
	Central Pacific LF	*ACV* Providencia	*SST*	*P* Palo Seco	*ACV* Londres	*ACV* El Rey
Pearson r	*ACV* Providencia		0,06	-0,38	0,20	0,38
	SST	0,01		0,04	0,26	0,06
	P Palo Seco	-0,33	0,00		-0,67	-0,34
	ACV Londres	0,30	0,23	-0,69		0,52
	ACV El Rey	0,43	0,05	-0,36	0,48	

As it can be seen in Table 5.1 the results of the Spearman r_s hardly vary from the results of the Pearson r (~ 5 %) and show comparability due to their similar values for all derived correlation matrices. Therefore, tested indices were found to be of a linear character and of proper use for the Pearson r.

c) test on normal distribution

Several statistical methods were tested on normal distribution to reveal skewness of implemented hydrological and climatic data series, which is particularly for hydrological time series questionable:
- Shapiro-Wilk test (1965)
- frequency plots with fitted normal distribution

Generally can be said that except for climate station “San José” (Central Valley) the precipitation anomaly series are according to the Shapiro-Wilk test results (probability for normal distribution p ≥ 50 % with at least 95 % confidence; Conover, 1999) approximately normal distributed.

The following figure (Fig. 5.6) gives a histogram of plotted frequencies with fitted normal distributions for each index applied in this study in order to demonstrate skewness of hydrological-atmospheric data series.

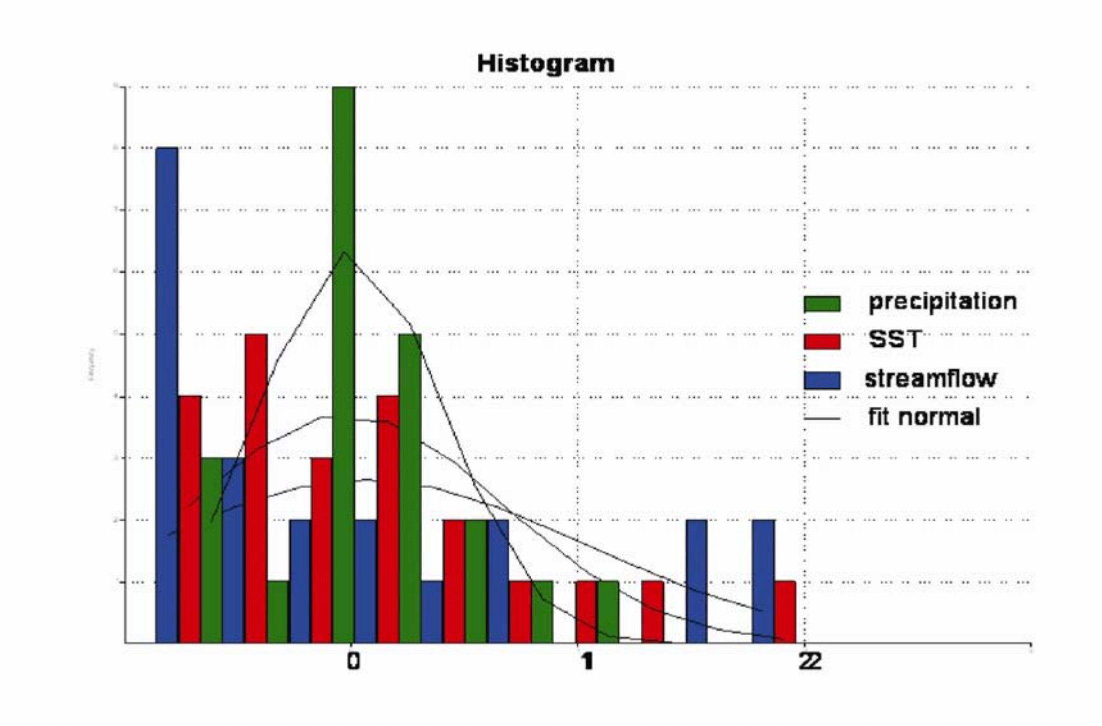


Fig. 5.6 Low flow season plotted frequencies with fitted normal distributions of representative stations of the North Pacific region for:
- o precipitation anomalies *(green)* for the period 1973-2003 (station Nicoya, Santa Cruz)
- o SST *(red)* for the period 1973-2003
- o streamflow anomalies *(blue)* for the period 1973-2003 (station Rancho Rey, Guardia)

The histogram in Figure 5.6 clearly shows the right skewed frequency of SST and ACV and would suggest a transformation process in order to normalise data series. This was done by a log-transformation on the original maximum and cumulated drought indices (AMD, ACD, AMV and ACV), unfortunately without better Shapiro-Wilk test results. Despite these contradictory facts, it was decided to realise the correlation study with standardised, but non-normalised, data series. This must be considered for interpretation.

The correlation matrices were calculated separately for each season, either high flow season (HF) or low flow season (LF), corresponding to their climatic region (North Pacific, Caribbean etc.). Involved are all available atmospheric and hydrological anomaly series (SST, ACV and precipitation P) derived according to fulfil above discussed statistical requirements such as no autocorrelation, linearity and normal distribution. The ACV drought anomaly index was chosen representative for this correlation study due to the fact, that the ACD index shows similar behaviour.

Moreover, the SST 3.0 index compared to e.g. the SOI shows higher correlations with in this study implemented hydrological indices (P, ACV). This result led to discard displaying the SOI, despite significant correlations.
The Pearson r matrices additionally come with a comparative value, the probability of non-correlation *p (uncorrelated)* between two data series in order to facilitate interpretation of correlation coefficients r.

Four correlation matrices (Tab. 5.2, 5.3, 5.4 and 5.5) were separated and seasonally displayed below to discuss presumed interactive relations for different climatic regions (North Pacific and Caribbean) of opposite drought behaviour.
Describing the correlation matrices requires being aware of the in this study applied calculation procedure. The Pearson r can be of negative and positive signature, which signifies in the case of a negative sign a contrary linear relationship. This will say if one data series at one point shows a maximum, while the neighbour series contains a minimum at the same data point, both series are negatively correlated with each other.

What does this mean for interpreting a linear correlation analysis of atmospheric-hydrologic interrelations?

A positive character of the drought anomaly index reflects drier than normal streamflow conditions and when circumstances are “wetter” than the mean drought the index becomes negative. Precipitation anomalies show the contrary picture; here a negative sign indicates drier condition and a positive sign wetter condition. The sea surface temperature (SST) anomaly shows positive values during an active El Niño phenomenon (warm phase) and negative values for La Niña conditions (cold phase).

The literature mentions various studies (Retana, 1999; Ropelewski & Halpert, 1996 a.o.), which discovered the warm El Niño phase to be responsible for lower than normal precipitation during wet season (at the Pacific; more precipitation than normal at the Caribbean). If this proclaimed condition is given, streamflow and precipitation also can be assumed to show deficits (increase at the Caribbean).
This might be reflected by a negative correlation coefficient (positive r for the Caribbean) for precipitation anomaly and SST index. ACV index correlated with SST should result in positive coefficients (negative r for the Caribbean), if there is such effect on streamflow.

Tab. 5.2 North Pacific low flow seasonal (LF) correlation matrix for:
- *ACV* anomalies of station Rancho Rey and Guardia for the period 1973-2003
- *SST* 3.0 departures for the period 1973-2003
- precipitation *P* anomalies for station Nicoya and Santa Cruz for the period 1973-2003

correlation matrix	**p(uncorrelated)**					
Pearson r	**North Pacific LF**	*ACV* Rancho	*SST*	*P* Nicoya	*P* Santa Cruz	*ACV* Guardia
	ACV Rancho		0,40	0,04	0,20	0,03
	SST	0,23		0,71	0,20	0,1
	P Nicoya	-0,53	0,11		0,00	0,07
	P Santa Cruz	-0,35	0,35	0,70		0,94
	ACV Guardia	0,56	0,40	-0,48	-0,02	

Tab. 5.3 North Pacific high flow seasonal (HF) correlation matrix, respectively

correlation matrix	**p(uncorrelated)**					
Pearson r	**North Pacific HF**	*ACV* Rancho	*SST*	*P* Nicoya	*P* Santa Cruz	*ACV* Guardia
	ACV Rancho		0,42	0,75	0,77	0,39
	SST	0,22		0,00	0,00	0,24
	P Nicoya	-0,08	-0,74		0,00	0,48
	P Santa Cruz	0,08	-0,69	0,79		0,78
	ACV Guardia	0,24	0,31	-0,20	0,08	

When a closer look is taken at the seasonal Pearson correlation matrices in Table 5.2 for low flow season and Table 5.3 for high flow season, mentioned interrelations above can be confirmed. The North Pacific high flow season (from June until December) is characterised by strong (r = -0,79; -0,69) negative correlations for the SST-P interaction. This perfectly coincides with earlier investigations (Retana, 1999 and Ropelewski & Halpert, 1996), which revealed lower precipitation during wet season at the Pacific Vertient.

Other high flow interactions like P-ACV anomalies do not show any specific relation (r < +/- 0,2), while SST-ACV moderately correlates (r = 0,22; 0,31). The drought behaviour of the two runoff stations (Guardia, Rancho Rey) in this region can be considered to be of a relatively distinct pattern (r = 0,24). The high season (HF) correlation matrix for the North Pacific (Tab. 5.3) was plotted graphically to better display interrelations and possible delays (Fig. 5.7).

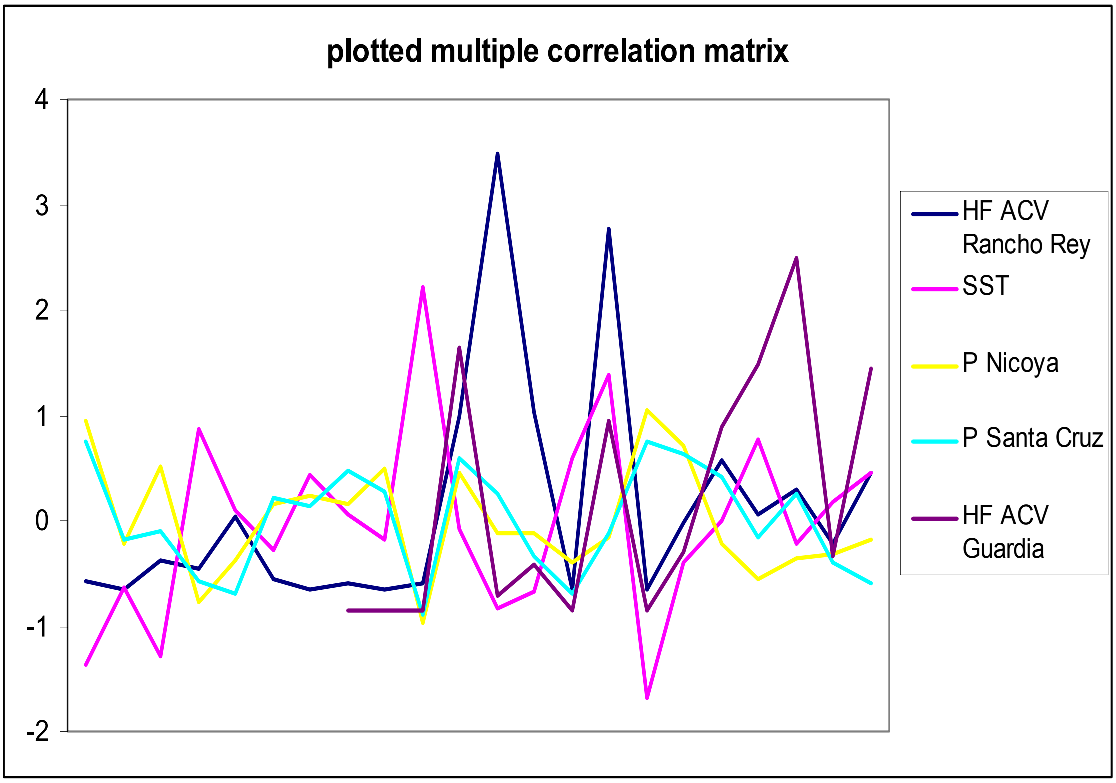


Fig. 5.7 Plotted North Pacific high flow (HF) season correlation matrix (1973-2003)

What might be confusing at first sight in Figure 5.7 shall give a visual perception of correlations. The yellow and light-blue (precipitation stations) graphs coincide in their oscillation (r = 0,7) and contrast the pink graph (SST). A SST-maximum is characterised by a P-minimum and the other way round, which manifests in a strong negative correlation (r > -0,69) and signifies less precipitation during wet season at the North Pacific. The other graphs do not or just moderately correlate (r ~ 0,2), but give certain interesting tendencies in order to hydrologically verify their interrelations.
Negative precipitation anomalies reflect less rain than normal and result in drier than normal streamflow conditions (positive values of ACV anomalies, dark-blue and brown graphs). A warm El Niño phase (positive SST-pink graph) coincides with drier than normal ACV values containing a shift in time lag, which causes significant, but moderate correlation coefficients (r = 0,22; 0,31).

This delay of streamflow drought on the SST signal could not clearly be quantified. The approach to determine the degree to which two time series are correlated estimates cross-correlation coefficients r (d) for every delay d time step according to the following procedure:

$$r(d) = \frac{\sum_i \left[(x_i - \mu) * (y_{i-d} - \mu)\right]}{\sqrt{\sum_i (x_i - \mu)} \sqrt{\sum_i (y_{i-d} - \mu)^2}} \qquad \textbf{(5.2)}$$

, where x_i and y_i are different time series (-) and respectively their means μ (-).

The following Figure 5.8 shows for representative stations according to climatic regions the cross-correlation r (d) plots for SST - LF ACV's (period 1973-2003).

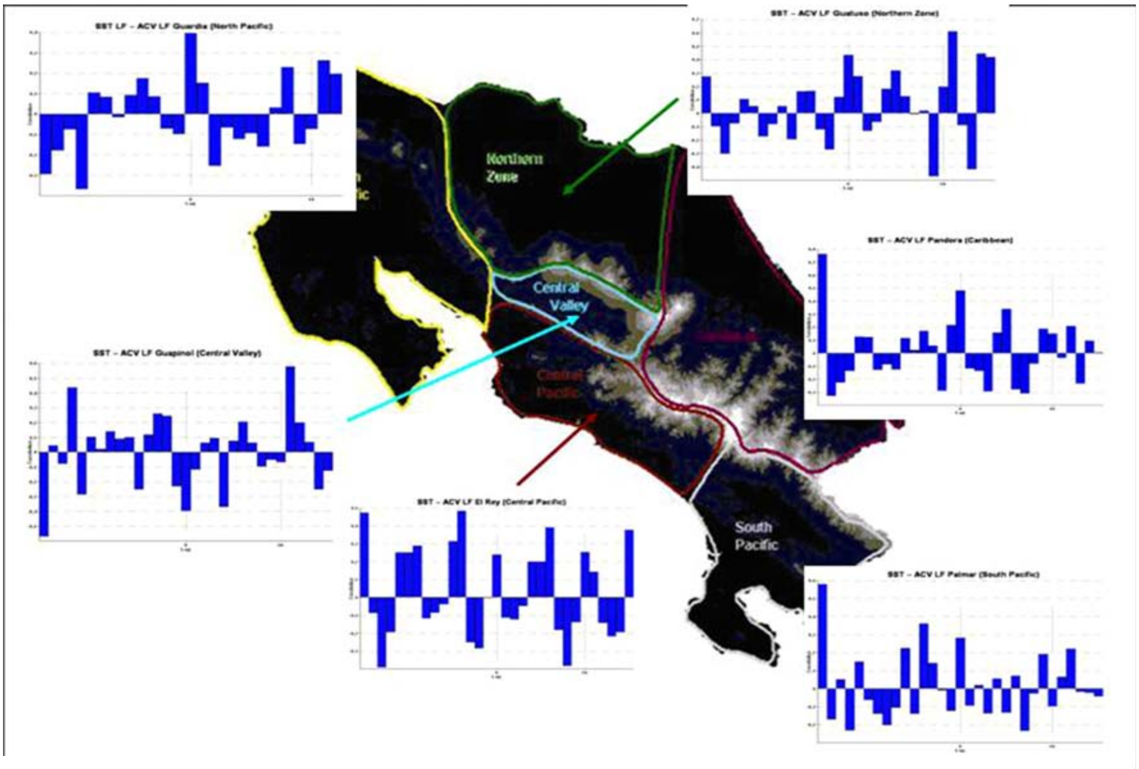


Fig. 5.8 Plotted cross-correlation coefficients r (d) for SST and low flow seasonal ACV (LF) for the period 1973-2003 across climatic regions (one bar = one time lag)

The graphical plots of r (d) in Figure 5.8 do not show a significant, recognisable spatial and temporal pattern. The ENSO index is characterised by a very inconsistent, in quantity seasonally varying signal. Nonetheless, the correlation maximum does not show a shift in time, which can be presumed a direct effect of ENSO on drought or shifts in time seem to be active for not more than one year.

For the time lag-zero most stations show their correlation maximum for, at least a period of five years (time lag five). Exceptions are stations at the Central and South Pacific, where a shift in time of four years reveals a maximum correlation. In both cases, lag four r (4) stands for a four year delay and signifies that streamflow drought appears four years after the SST maximum. Here, a persistent behaviour of streamflow drought can be assumed. However, a temporal resolution of one year time lags can be considered too low to detect interseasonal delays and a delay of more than four years maintains questionable.

This means, that streamflow droughts can persist interseasonally and interannually from one year up to four years leaving the theory of high flow season as major recharge period and responsible for later drought development still valid. Plotting calculated high flow seasonal cross-correlation coefficients exhibit the same low resolution and are not presented here.

The Caribbean low flow season reveals no significant ENSO (SST) correlation in precipitation series (r = 0,11; 0,35), but drought indicators (ACV) highly coincide with precipitation due to its negative coefficients (r = -0,35 to -0,53). The drought series in Table 5.5 signal a positive correlation with El Niño through r = 0,23 and r = 0,40, which assumes interseasonal dependence on the ENSO phenomenon.

The Caribbean were chosen due to their contrary climatically behaviour. Retana (1999) found out that a warm ENSO phase coincides with high probabilities for a wet event at the Atlantic Vertient. The high flow seasonal correlation matrix (Tab.5.4) shows a strong (r = 0,55) "wetter than normal" relation between the El Niño signal (SST) and precipitation deviation (P Limón). The hydrological cycle (P Limón-ACV) does not reveal any significant relationship (r < 0,2), except for station "Pandora" (r = -0,22). The latter station also reacts in contrast to the others corresponding to its relation to SST (r = -0,39).

Tab. 5.4 Caribbean high flow seasonal (HF) correlation matrix between:
- *ACV* of station Pandora, Palomo, Oriente and Dos Montañas for the period 1973-2003
- *SST* 3.0 for the period 1973-2003
- *P* of station Limón for the period 1973-2003

correlation matrix		**p(uncorrelated)**					
	Caribbean HF	*ACV* Dos Mont.	*SST*	*P* Limón	*ACV* Pandora	*ACV* Palomo	*ACV* Oriente
	ACV Dos Mont.		0,37	0,94	0,33	0,00	0,02
Pearson r	*SST*	0,12		0,01	0,07	0,11	0,16
	P Limón	0,02	0,55		0,32	0,81	0,81
	ACV Pandora	-0,22	-0,39	-0,22		0,98	0,43
	ACV Palomo	0,58	0,26	0,06	0,00		0,00
	ACV Oriente	0,51	0,16	0,05	-0,18	0,61	

The negative correlations in Table 5.4 signify "wetter than normal" precipitation or streamflow conditions, while the other stations follow a slight-positive "drier than normal" correlation, which obviously does not coincide with the region's climatic characteristics.

Low flow seasonal correlations (Tab. 5.5) seem to confirm this contrary picture. Station "Pandora" shows absolutely no relation, neither to precipitation anomalies P nor to ENSO. High positive correlations (r = 0,28; 0,54 and 0,79) can be found for the SST-ACV relationship, which tends to contradict earlier studies and is confirmed by relatively high coefficients (r = -0,41) for the hydrological cycle (P Limón-ACV).

Tab. 5.5 Caribbean low flow seasonal (LF) correlation matrix, respectively

correlation matrix	**p(uncorrelated)**						
	Caribbean LF	*ACV* Dos Mont.	*SST*	*P* Limón	*ACV* Pandora	*ACV* Palomo	*ACV* Oriente
	ACV Dos Mont.		0,40	0,05	0,29	0,02	0
Pearson r	*SST*	0,28		0,52	0,82	0,00	0,07
	P Limón	-0,41	0,14		0,83	0,56	0,05
	ACV Pandora	0,23	-0,05	0,05		0,63	0,41
	ACV Palomo	0,50	0,79	-0,13	-0,11		0,07
	ACV Oriente	0,74	0,54	-0,41	0,18	0,38	

Summarised can be said, that just one Caribbean runoff station (Pandora) follows expected relations for the SST signal resulting in higher precipitation and streamflow conditions during a warm phase event for high flow season. The other three stations (Oriente, Palomo and Dos Mont.) seem to be more afflicted to yet unknown climate phenomena for low flow season, which competes with the ENSO signal and tends to diffuse results. Furthermore, it might be presumed, that these stations are more affected by cold phase events (La Niña) or other atmospheric circulation patterns, such as the North Atlantic Oscillation Index (NAOI).

Sun & Furbish (1997) found “drier than normal”-streamflow and precipitation conditions during La Niña events for Florida, which can be assumed to climatically coincide with the Central American Caribbean. At that point, explaining a drought mechanism for the Caribbean according to a single, diffusive atmospheric circulation signal (SST) seems to be not adequate.
Tab. 5.6 below presents a summary of the correlation study regionally separated into climatic zones of similar behaviour. **c** counts for a significant correlation coefficient r ≥ +/- 0,2 and **¢** is assumed to be of little or no association (r < +/- 0,2). All significant relations between the atmospheric circulation pattern displayed as sea surface temperature deviation index (SST) and the hydrological cycle (P, ACV) are listed in the table.

Tab. 5.6 Regionally seasonal (HF, LF) relations (**c** = r > 0,2) for the period 1973-2003 between:

- precipitation deviations (*P*)
- drought anomaly index (*ACV*)
- ENSO-signal (*SST*)

climatic region	***P/LF ACV***	***P/HF ACV***	***P/LF SST***	***P/HF SST***	***LF ACV/SST***	***HF ACV/SST***
Northern Zone	**no data**	**no data**	**no data**	**no data**	**no signal**	**no signal**
North Pacific	**c**	**¢**	**¢**	**c**	**c**	**c**
Central Valley	**¢**	**c**	**¢**	**c**	**¢**	**c**
Central Pacific	**c**	**¢**	**¢**	**c**	**¢**	**c**
South Pacific	**no data**	**no data**	**no data**	**no data**	**c**	**c**
Caribbean	**c**	**¢**	**¢**	**c**	**c**	**¢**

no data = no precipitation data available for correlation matrices
c = correlation, r > 0,2
¢ = no correlation, r < 0,2
no signal = indifferent ENSO signal

Remarkable is the interrelation of precipitation and sea surface temperature (P / SST) at the Pacific and Caribbean Vertient. Both regions follow “lower than normal” (Pacific) and “wetter than normal” (Caribbean) precipitation tendencies during active El Niño signals at low flow (LF) season, which is characterised by **c** (for correlation) in the table (Tab. 5.6). However, this picture is not always reflected in the ACV - SST correlation.

The North Pacific stations react on SST oscillations during low and high flow season (**c**). The Caribbean shows a contrary pattern, as there conspicuous “drier than normal” streamflow conditions during low flow season were discovered. The South Pacific is free of interseasonal variations and reflects the ENSO signal all year round. The Central Valley and Central Pacific region demonstrate correlations at high flow season and non at low flow season. The relationship between atmospheric circulation patterns (ENSO) and seasonal streamflow drought anomaly indices (LF, HF ACV and ACD) can be better spatially demonstrated by displaying calculated Pearson r correlation coefficients for the runoff station’s catchments at a national scale. The regionalisation (IDW) in Figure 5.9 is exclusively used to better reveal spatial behaviour.

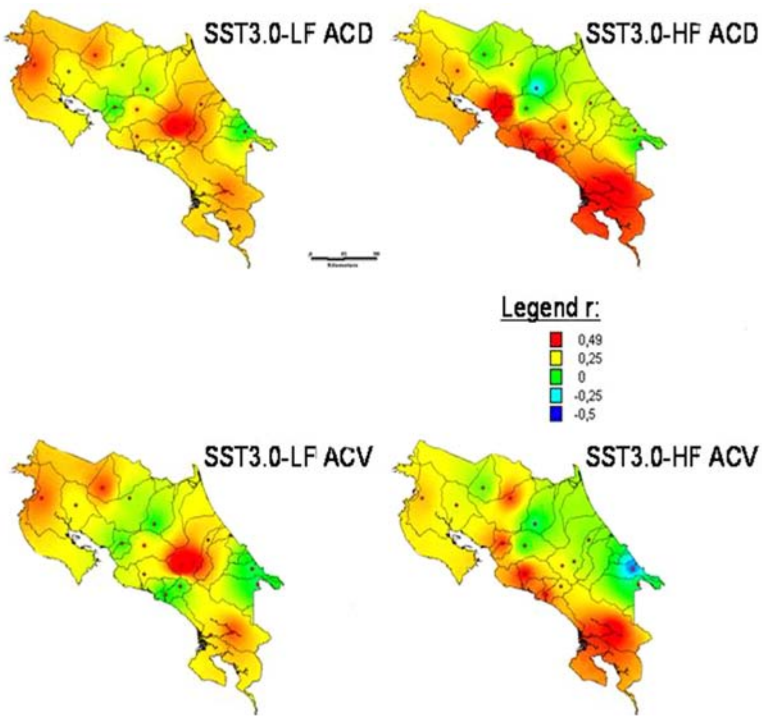


Fig. 5.9 Regionalised correlation coefficients r for SST 3.0 and seasonal drought anomaly indices (LF-left panel, HF-right panel, ACD-upper panel and ACV-lower panel)

The different drought anomaly indices (ACV, ACD) show an identical relation with the sea surface temperature index (SST). Therefore, it was considered sufficient to concentrate on the spatial interpretation of just one anomaly index (ACV). The streamflow seasons (HF, LF) within the hydrological year coincide in their spatial correlation pattern, but in the term of quantity can be seen discrepancies.

Generally correlates the Pacific Vertient with the SST-ENSO signal in Figure 5.9, except for the Central Valley. The main active El Niño-phase can be noticed due to more significant correlations for high flow season.

The mountainous region of the Caribbean Vertient highly correlates with SST during low flow season, which diminishes during high flow season. The Northern Zone shows indifference for the SST signal throughout the year and ENSO is supposed not to be a major effect on drought behaviour of this region. The South Pacific shows high correlations for the SST without seasonality and seems to function as the most directly affected region of Costa Rica by the El Niño oscillation. Another numerically atmospheric circulation pattern (NAOI) was applied at the Caribbean Vertient due to inconsistencies in preceding correlation results.

The NAOI has been described as the most important mode of climate variability in the North Atlantic (Murphy and Washington, 2001). The NAO index, defined here as the SLP difference between the Azores High and the Icelandic Low, describes the grade of a north-south atmospheric pressure gradient across the North Atlantic Ocean (Fig. 5.10). The NAO shifts between its modes of variability changing wind speed and direction at the North Atlantic Ocean that affect heat and moisture transport to the surrounding continents and seas.

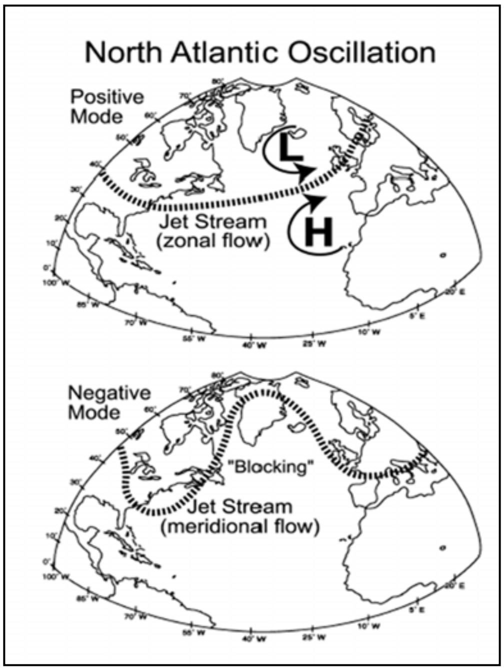


Fig. 5.10 The North Atlantic Oscillation (NAO) pattern, after Bradbury et al. (2002)

The strength of the NAOI is determined using an index of the difference between the normalised sea level pressure between the Azores (or Portugal) and Iceland.

High positive NAOI values are associated with stronger than average mid latitude westerlies and a corresponding tendency for milder, wetter winters in the United Kingdom and Northern Europe (Wilby *et al*, 1995). The NAOI is presumed to be strong enough to affect climate variability at the Caribbean evolving in a similar manner to ENSO with SST and precipitation anomalies over the region.

Colman and Davey (1999) related SST anomalies in the North Atlantic to temperature and precipitation anomalies over Europe. They found that summer climate over much of northwest Europe could be predicted from winter SST anomalies. Warm summers were linked to the movement of anomalously warm water across the North Atlantic from the east coast of the USA to northwest Europe during the spring months.

Indeed, Bradbury et al. (2002) found significant correlations occurring in winter (January - March) between the NAO index and lower than normal monthly streamflow at New England (USA) western inland locations, which can be compared to the Costa Rican correlation analysis. A mechanism explaining how negative NAO winter (January - March) conditions can be translated into lower streamflows at the Caribbean, involves the position of the polar front jet.
When the NAO is negative, the Icelandic Low is abnormally high and farther to the southwest of Iceland (see Figure 5.10 above, lower panel). This leads to a weakening of this low, which can be associated with meridional flow in the North Atlantic region resulting in a position of the polar front jet farther south than normal.
Caribbean precipitations usually occur in the period from December to March due to the shifting south ITCZ (Chapter 2.3.1), which brings trade winds to transport large moisture masses towards the Atlantic coast. Under these conditions it is likely possible, that the polar depression (negative NAOI mode) forces a change in storm-tracks, storm-frequency patterns and disturbs the usual ITCZ track, which is supposed to be linked to regional climatic patterns at the Caribbean (Coen, 1951 and 1971; Hastenrath, 1967). Results are assessed in regionally displayed figures (Fig. 5.11) to better reflect spatial relations and in plotted correlation matrices to display possible time lags (Fig. 5.12). At that point, the correlation of Caribbean low flow ACV's (winter season in Europe) with the corresponding seasonal NAOI reveals a strong association (r ~ -0,5) as it can be seen in Figure 5.11.

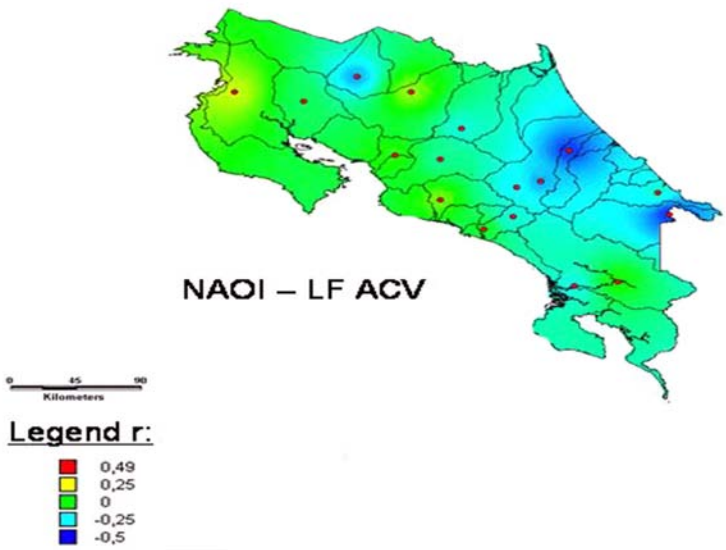


Fig. 5.11 Correlation Coefficients r for NAOI and seasonal drought anomaly indices (LF-left panel, HF-right panel ACV) for the period 1973-2003

The negative correlations (blue) reflect low flow seasonal streamflow drought conditions at the Caribbean, which confirms the conspicuous correlation results for the ENSO signal SST and assumes both oscillation patterns, ENSO and NAOI to influence Caribbean low flow seasonal climate variability.
Figure 5.12 compares the atmospheric oscillation indices SST (light-blue graphs) and NAOI (dark-blue graphs) with Caribbean components of the hydrological cycle (pink graphs) separated into low and high flow season. Precipitation anomalies (P Limón) react in distinct manners on the oscillation signal. As earlier mentioned above P Limón is highly positive correlated (r = 0,55) with the Pacific sea surface index for high flow season (see lower left panel), which signifies more than normal precipitation during active El Niño phases.

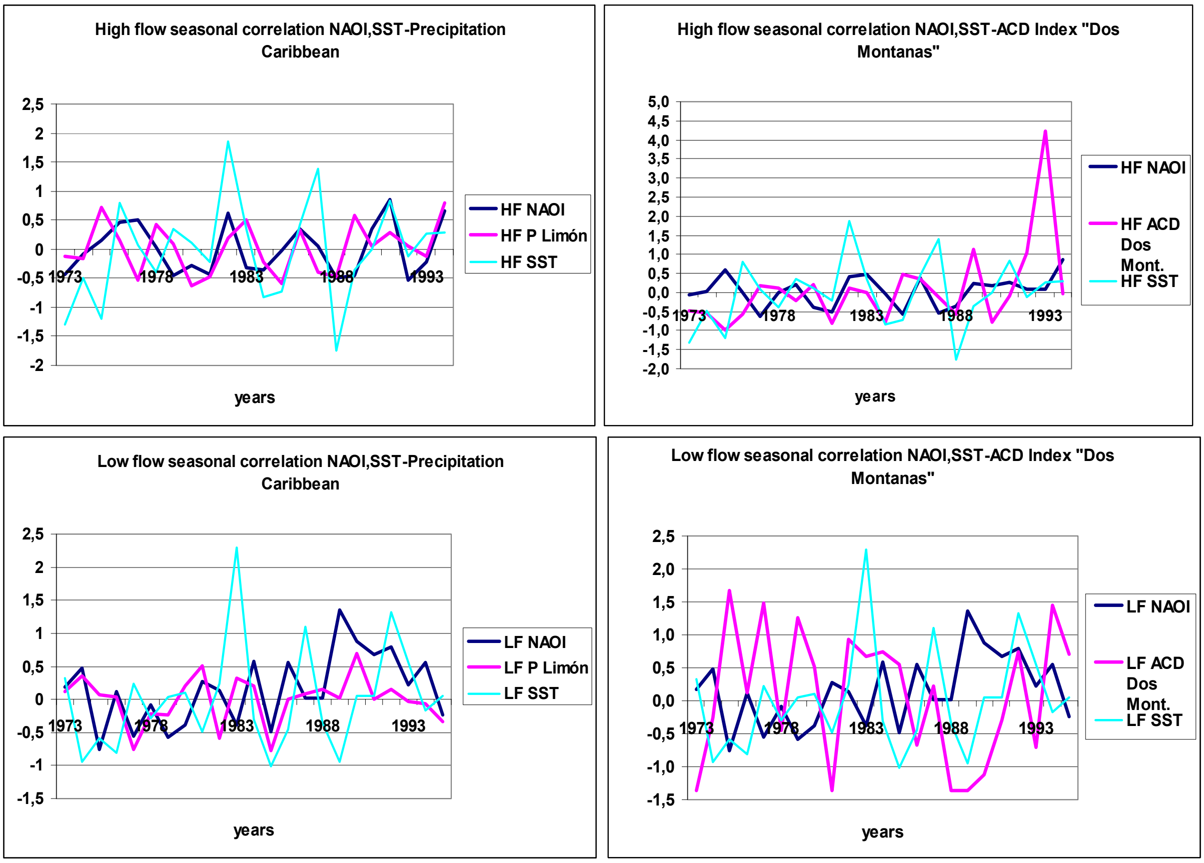


Fig. 5.12 Plotted seasonal (LF-lower panels, HF-upper panels) correlation matrices for the period 1973-2003 between:
- o NAOI
- o SST 3.0
- o P Limón (left panels)
- o ACD of station “Dos Montañas” at the Caribbean (right panels)

The SST - P Limón seasonality (LF) in Figure 5.12,respectively does not play an important role due to a low insignificant (r = 0,14) correlation coefficient. The NAOI highly correlates with precipitation (r = 0,44) for low flow season, which means due to the contrary orientation of the oscillation indices less than expected rainfalls (see upper left panel) and seems to compete with the SST for drier conditions during high flow season (LF NAOI - P, r = 0,34). The low flow (LF) seasonal NAOI was plotted against the LF ACD Index to better reveal streamflow drought interrelation.

The upper right panel of the Figure 5.12 shows a significant negative correlation (r = -0,45) for NAOI - LF ACD and also a significant correlation for SST - LF ACD (r = 0,32) indicating that drought anomalies strongly coincide with the North Atlantic and South Pacific Oscillation patterns, which favours in both cases towards drought.
The NAOI seems to get negative during El Niño and positive for La Niña events following the SST signal at low flow season. It might be presumed that a warm ENSO phase (El Niño) occurring during low flow season coincides with a polar depression causing lower than normal streamflow conditions.

High flow season can be said to highly reflect significant interrelation correlations for both atmospheric patterns with precipitation (NAOI - P Limón, r = 0,31) as it can be seen in the lower right panel of Figure 5.12, while streamflow drought behaviour seems to be uninfluenced by such circulation patterns (see upper right panel).

Generally can be said that the NAOI is assumed to reflect especially low flow seasonal Caribbean drought occurrence more adequately than the SST. ENSO is proven to be responsible for wetter than normal precipitation conditions, which is not representative for streamflow data. Both drought and flood, severe hydrological extremes can occur in one year without interseasonal persistence due to an active annual recharge.
Moreover, the connection of the Atlantic Ocean oscillation, responsible for tropical Caribbean climate variability is directly linked to hydrological variability in extra-tropical regions like Europe, which tries to adduce the following Chapter 4.4.

5.4 Link to drought characteristics in Europe

The relationship between the North Atlantic Oscillation Index (NAOI) and Caribbean climate variability might bridge the gap to European drought characteristics. The chapter above (4.3) clearly describes the NAO influencing temporal and spatial drought patterns of Costa Rica.

The main conclusions of the correlation study with the North Atlantic Oscillation above are of following spatial and temporal characteristics:

- NAOI is mainly linked to the Caribbean and shows negligible effects at the Pacific Vertient.
- Strong correspondence on streamflow drought seasonality; low flow seasonal drought behaviour coincides with NAOI (r > -0,5) supported by the correlation with P (r = 0,44), while high flow season can be supposed to be free of influence (r < -0,2).
- North Atlantic Oscillation can be connected to the South Pacific Oscillation (r = 0,28) and coincides with the occurrence of major El Niño and La Niña events.

The latter point can be demonstrated by plotted seasonal oscillation indices (Fig. 5.13). This figure shows the Caribbean low flow season from December to May (1.12.-31.05.), NAOI, SOI and SST 3.0. The major El Niño events of the years 1982/83 and 1997/98 obviously can be associated with the NAOI according to the figure and its significant, but moderate Pearson correlation coefficients r (NAOI - SOI) = 0,28 and r (NAOI - SST) = -0,18.

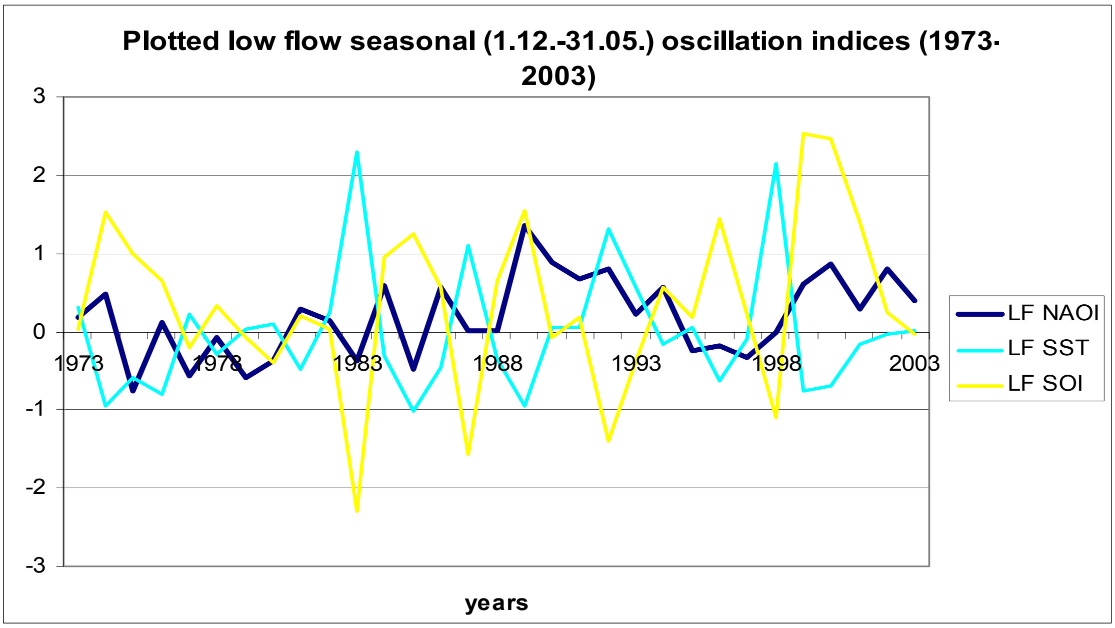


Fig. 5.13 Plotted low flow seasonal (LF) oscillation indices for the period 1973-2003

As earlier mentioned various authors (Wilby et al., 1995; Shorthouse et al., 1997; Colman et al., 1999; Stahl, 2001; Wedgbrow et al., 2001 and Lloyd-Hughes, 2002) describe a significant relation of oceanic oscillation on European climate variability and use this dependency to develop e.g. long-range forecast models. The oscillation either can be of Atlantic or Pacific type, better known as e.g. North Atlantic Oscillation (NAO) or South Pacific Oscillation (ENSO).

ENSO is known to exert an influence outside the tropical Pacific, even as far as Europe (van Oldenborgh et al., 2000). Atlantic oscillations or other circulation patterns are considered more suitable to investigate European climate variability, because ENSO teleconnections are influenced by extra-tropical sea surface temperature interferences.
A positive NAO index causes unrestrained flow of warm and moist maritime air derived from westerlies blowing over the Gulf Stream across the North Atlantic bringing relatively mild winters into northern Europe.
When the NAO index is negative, Europe and Scandinavia has been known to receive below-normal temperatures (2 – 4 °C) and significantly less precipitation (50 % to 75 % less) than during positive NAO winters (Kushnir, 1999). Shorthouse & Arnell (1997) confirmed this influence by showing a link between the NAOI and averaged monthly runoff across Europe.

These correlation results might not directly be comparable to Costa Rican r values due to distinctive derivation procedures. It is to presume that averaged monthly runoff indices produce higher r values than averaged drought anomaly indices.

The “signal” from an ENSO event usually reaches the extra-tropics during the "mature phase" of ENSO immediately followed by an event year (Diaz and Markgraf, 1992). Hence, teleconnections between ENSO and mid-latitude climates are typically most apparent during winter. The El Niño Southern Oscillation (ENSO) is seen according to Lloyd-Hughes (2002) to exert a significant influence on European drought. A spatial restriction is made to the central western and eastern European region during spring months. Lloyd-Hughes (2002) adds in his study on meteorological drought in Europe, that ENSO itself is not a primary cause of drought, but more a moderating factor of existing conditions.

Stahl et al. (2001) correlated monthly averages of a regional streamflow deficiency Index to NAOI for clustered European regions. In this study low correlations were found for the whole time series applying different lags and averaging periods (maximum r < 0,32 for the UK). Seasonal negative correlations were much higher for the winter season of most of the regions indicating more than normal precipitation, except Spain correlated significantly positive with NAOI coinciding with streamflow deficiency.

This can be presumed to be comparable to Costa Rican results due to the significant relation coinciding with streamflow drought in terms of determined season and averaging interval. Generally can be said that the results of such correlation analysis strongly vary with the determined season and averaging interval. It can be seen as feasible to compare correlations across different continents between basin-wide teleconnection indices as e.g. for the NAOI, when such assumptions are considered.

Table 5.7 compares reported European and Costa Rican droughts with the occurrence of El Niño years.

Tab. 5.7 Reported drought events in Europe and Costa Rica (1970-2000) associated with El Niño events modified after European Environmental Agency (2001) and CEPREDENAC (2000)

El Niño:	drought in Europe:	drought in Costa Rica:
1972	USSR	*no drought reported*
1973	North and east Europe	Moderate drought North Pacific
1976	Northern Europe	*no drought reported*
1977	UK, Scotland	*no drought reported*
1982	*no drought reported*	moderate drought Central Pacific
1983	*no drought reported*	severe drought North Pacific
1987	*no drought reported*	*no drought reported*
1988	Most of Europe	*no drought reported*
1992	Northeast Germany	moderate drought North Pacific
1993	Spain, Portugal, east Europe	*no drought reported*
1997	France, UK, Portugal, Germany	severe drought most of the country
1998	*no drought reported*	severe drought most of the country

5.5 Summary

Chapter 5 clearly shows a strong influence of atmospheric circulation patterns on regional streamflow drought behaviour. This influence can be seen as of most direct character affecting drought in Costa Rica at an interseasonal scale without indication of multi-year persistence in the hydrological system. The correlation study revealed a spatial pattern of varying dependence on Pacific and Atlantic Oscillation across Costa Rican streamflow stations. The El Niño-Southern Oscillation (ENSO) mainly affects the Pacific Vertient, while the Caribbean exhibits a strong influence of the North Atlantic Oscillation (NAO).

The El Niño-oscillation demonstrates the strongest impact on the hydrological cycle of the region. Particularly for the Caribbean region, the ENSO pattern in conjunction with the NAO is assumed to fortify extreme hydrological events. Both circulation patterns can be considered to follow more or less a global scheme producing teleconnections worldwide, as for Costa Rica.

Nevertheless, it might be difficult to talk about atmospheric circulation patterns causing streamflow drought. Many regional or local physiographic and climatic characteristics play a very important role on temporal and spatial drought behaviour of river flows. Obviously, Costa Rica's climate is extremely sensitive to subtle changes in the relationships between the Pacific and Caribbean air masses, and the northern and southern air masses. Disruptions caused by El Niño have a direct impact on day to day, and season to season climate, which results in cross-correlation time lags of less than one year for SST - anomaly indices correlations.
Therefore, the main cause of interseasonal drought persistence can be seen in regional physiographic catchment's characteristics such as large reservoirs. In fact, it is considered more appropriate to discuss about such teleconnections in the sense of atmospheric circulation patterns *strongly influence* Costa Rican drought behaviour instead of causing it.

It could be showed that all major drought events coincide with the occurrence of a warm El Niño-phase, which even can be transmitted to the extra-tropics as far as Europe. Containing certain influence from this tropical oceanic oscillation pattern combined with disturbing Atlantic patterns the strongest El Niño events are reflected in European drought occurrence (Tab. 5.7).
Spatial and temporal drought patterns as earlier mentioned in this chapter, show many regional and even local phenomena modifying global influences such as circulation patterns. Flow regimes clearly depend on preceding precipitation regimes and frequencies, which are mainly produced by the movement of the ITCZ and topography.

The atmospheric circulations (ENSO, NAO) are considered to weaken this regional climate pattern (ITCZ) in order to provoke major changes in precipitation frequencies by maintaining the annual regime. Short and very intensive rainfalls combined with long dry spells are assumed to complete with lower groundwater recharge especially during high flow season, which is considered recharge season at the Pacific Vertient. At the Caribbean, generally higher annual rainfall and less monthly variability in precipitation frequencies throughout the year can be assumed to decrease seasonality in recharge. If there occurs any long-term precipitation deficit affecting regional recharge of reservoirs, conditions for streamflow drought might be prepared.

Physiographic catchment's characteristics such as large, effective reservoirs play a very strong role in drought development due to their ability of persisting climate variability at an interseasonal time scale (see Figure 5.14 lower panel). Reservoirs might resist an ongoing meteorological drought or prolong an active streamflow drought into the next season, despite higher precipitations, as it can be noticed frequently at the North Pacific region. Nevertheless, interannual persistence could not be revealed according to cross-correlation analysis. Persistence at a temporal scale is assumed to be limited to the next recharge period.

The cause of Costa Rican streamflow drought behaviour can be considered a conjunction of above mentioned distinctively-scaled factors like circulation patterns (global scale: Oceanic oscillation patterns – upper panel; regional scale: ITCZ movement – middle panel, Figure 5.14) affecting regional climate variability (precipitation regime and frequency), which is modified by regional and local physiographic catchment's and climatic characteristics (Fig. 5.14).

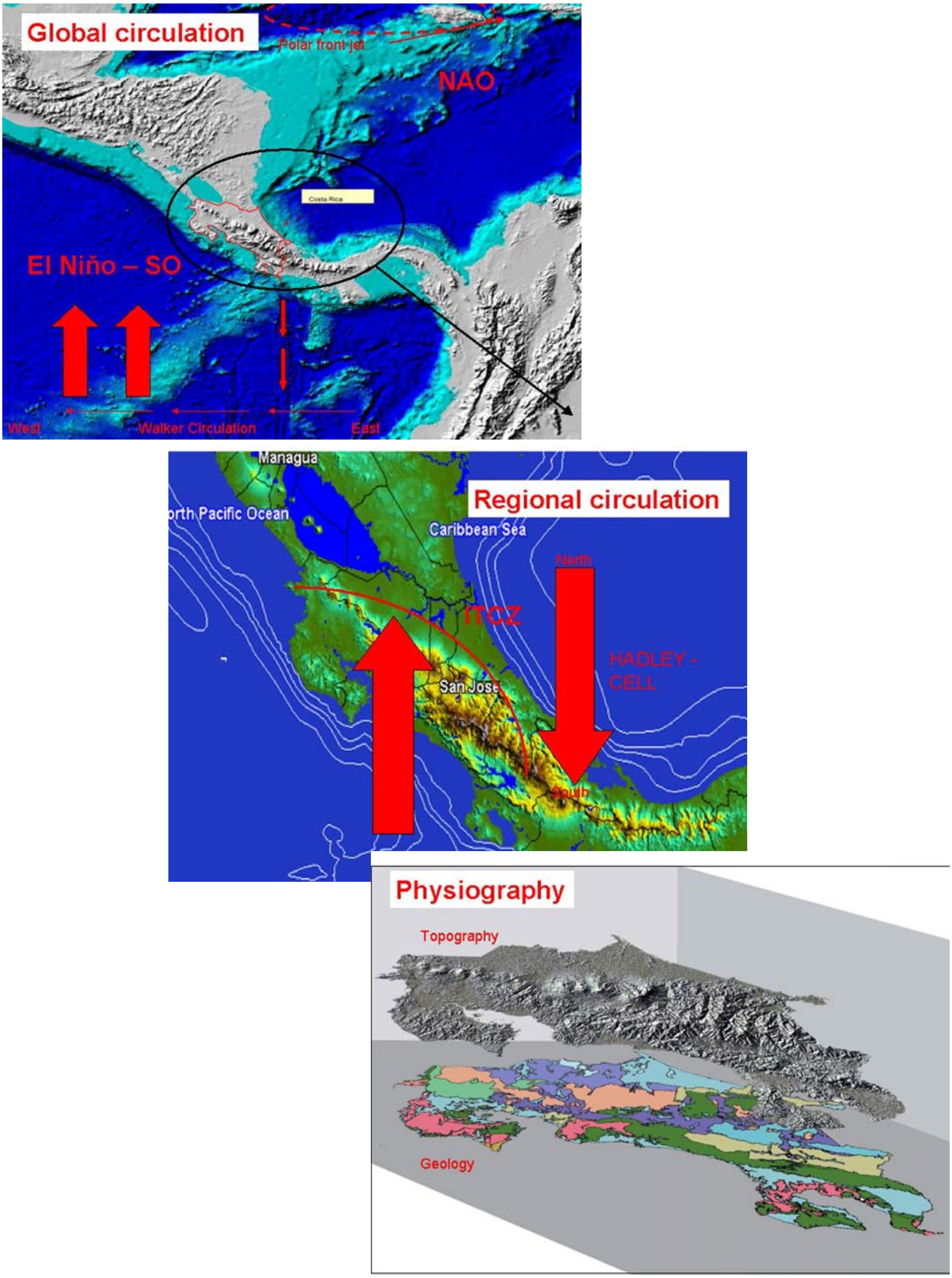


Fig. 5.14 Conjunction of drought influences at different temporal and spatial scales

6 Conclusions

The concrete objectives of this study were to determine temporal and spatial drought patterns by translating the threshold level approach to tropical Costa Rica, to realise a trend analysis if whether streamflow drought in Costa Rica has become more severe or frequent and to link drought indices to atmospheric circulation patterns in order to find drought causing influences. Furthermore, in this section the main results of presented methodologies are discussed proposing their ability for further investigations.

With the availability of seventeen gauging station's daily discharge series, the seasonal constant threshold level approach could be used to define drought events and to obtain a dataset of drought parameters indicating comparable extreme dry periods across Costa Rica's principal climatic regions, physiographic characteristics and flow regimes.

Analysing the dataset of drought indices for the period 1973-2003 obtained from seasonal threshold levels, typical temporal and spatial patterns could be found. Seasonality of streamflow drought can be generally described as droughts of long duration and low deficit volume occur during dry season and droughts of short duration and high deficit volume cluster in high flow season. Although a general distinction in dry and wet years for common period (1973-2003) across all country's stations was possible, the inter- and innerseasonal occurrence of drought periods varies considerably among the stations.
Derived anomaly indices permitted an assessment of "real" drought severity experienced in the catchments and revealed dependent on the climatic region typical temporal patterns of dry periods in high flow season. Droughts at the beginning of wet season can be seen as a prolongation of the preceding dry season, droughts during the main recharge period from August until November and droughts affected by the regional "little summer" climatic variation. Both, the latter high flow season drought typing can be assumed to mainly affect recharge and cause drought development for dry season. All stations were tested on persistency and could be presumed to be of non-persistent behaviour with minor exceptions. They can be principally explained by physical characteristics such as natural storage capacity causing certain memory in the hydrological system.

Spatial patterns could be drawn by analysing maximum drought events, drought variability, sequences of dry years (e.g. 1991-1995) in the term of anomaly indices and drought risk. At the Atlantic Vertient (Caribbean and Northern Zone), drought behaviour generally differentiates towards less drought impact by the one at the Pacific Vertient due to distinct climatic characteristics, which can be seen in the spatial extension of occurring maximum droughts and drought variability.

Furthermore, the northern region of the Pacific contributing drainage area is more susceptible to droughts than the South Pacific region.
Regional drought development in time could be spatially displayed by plotting anomaly indices over sequences of dry periods obtained from the evaluation of dry and wet years. Result is a clear regionally developing drought movement, which might affect areas of normally low drought affliction such as e.g. the Northern Zone region and the Caribbean.
Drought risk analysis revealed a similar pattern. Estimated magnitudes of low flow season-drought indices for a return period of forty years (T = 40 years) clearly identified the whole north of Costa Rica including the Northern Zone region and parts of the Caribbean to run more risk for drought than the south of the country. Estimated magnitudes (T = 40 years) of high flow season-drought indices even bear more risk for drought on the whole country, which points at the importance of high flow season as the main recharge period of the region.

A trend analysis was carried out to prove the question if whether streamflow drought has become more severe or frequent in the last years. The common period 1973-2003 was utilised to calculate the non-parametric Mann-Kendall statistics. Although for Costa Rica as a whole no significant trends could be found, clear spatial patterns can be seen. Exclusively, two out of three stations at the Northern Zone region show a significant (α = 0,05) trend in terms of drought severity and frequency, whereas the Central Pacific region exhibits just a positive trend towards more severe and frequent droughts occurring. The Caribbean clearly tends towards less frequency. These results generally coincide with the perception of droughts might extend into regions of low or no drought experience.

Costa Rican streamflow exhibits significant correlations between tested atmospheric circulation patterns (ENSO, NAO) and seasonal streamflow anomaly indices (ACD, ACV) with a time lag of maximum one year. Depending on a clear spatial pattern, significant (α = 0,1) correlations of $r > 0{,}5$ could be revealed. The Pacific regions significantly interrelate with the Southern Pacific Oscillation. However, the Atlantic drought influence can be seen as strongly superposed by the North Atlantic Oscillation.

These pronounced, direct effects of climate variability on the hydrological cycle are considered worth the effort to develop a regional drought forecast model. Such a statistical approach could provide useful long-range hydrological information for a sustainable water management service. An effort to forecast hydrological drought is not yet realised for this region and scarcely described in literature. An early warning system would help to prevent socio-economic damages as they have been experienced in the past during major El Niño events in the years 1982/83 and 1997/98.

The knowledge and data obtained in this study can be assumed well suited to carry out such drought forecast based on drought anomaly indices presented in this work. Advantages of such anomalies are among others independence of any regional climatic influence to properly compare different watersheds. In fact, distinctive oscillation indices can be individually selected for single stations depending on the significance of their interrelation. The understanding of temporal and spatial drought behaviour could then be usefully implemented in modelling seasonal time series of drought indices. Moreover, such statistically described teleconnection patterns are assumed to be able to detect severe droughts according to predefined generalised temporal and spatial patterns.

The methodology of presented drought indices is well suited to describe and generalise temporal and spatial drought behaviour, but limited to the availability of streamflow data at the gauged site. Completion and extension of observed sites must be a future aim.

The need for more data and therefore a better understanding of drought patterns indicates to utilise regionalisation methods. The methodology of defined drought risk based on frequency analysis of extreme values provides great potential for regionalisation of drought indices. Regional frequency methods have been developed to utilise additional information from sites within the region to improve at-site estimates and to obtain estimates at sites without observations.

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Appendix

Tab. 2.2 Catchment's characteristics derived from thematic data in a GIS

WATERSHED	AREA (km2)	PERIMETER (km)	DRAINAGE DENSITY (km/km2)	MEAN ELEVATION (m)	MEAN SLOPE (%)	RELIEF RATIO (m)
1	1768	389	3,8	259	5,3	2600
2	4781	387	3,6	1072	11,4	3000
3	721	148	5,0	543	11,6	3400
4	200	80	3,9	560	12,2	1600
5	365	105	3,2	122	1,2	1700
6	213	96	3,9	125	0,9	900
7	2868	306	4,8	1054	8,4	3300
8	1417	231	3,2	1101	15,3	1800
9	878	207	4,8	995	12,3	2400
10	378	97	3,6	105	0,5	700
11	2643	280	5,6	486	5,2	2200
12	1643	218	3,2	106	0,3	600
13	1561	193	4,5	228	2,1	900
14	2589	268	3,0	304	3,2	2100
15	3357	313	3,8	203	2,5	2000
16	2061	216	5,6	315	3	1400
17	510	115	1,9	843	7,5	1300
18	1369	303	4,6	400	6	1600
19	4201	923	4,1	206	6,1	1400
20	465	139	4,4	787	8,5	2600
21	425	133	4,3	248	3,3	1400
22	2123	233	5,4	1054	7,3	2400
23	834	157	3,9	276	7,2	2200
24	1266	203	3,5	1164	14,4	3400
25	452	174	4,7	362	9	1300
26	2310	361	4,7	1297	4,4	2800
27	641	141	4,4	421	17,3	2100
28	508	146	4,3	884	11,7	3400
29	341	139	5,3	1146	12,6	2100
30	2803	285	3,0	177	14,2	3200
31	231	81	5,4	129	4,5	1600
32	259	121	2,0	562	2,5	2500
33	1719	206	5,5	816	4,5	2500
34	1283	255	4,8	103	9,3	2900
35	2303	259	5,7	254	0,1	2100
Mean:	1471	226	4,2	534	7,0	2097
Min:	200	80	1,9	103	0,1	600
Max:	4781	923	5,7	1297	17,3	3400

Tab. 3.1 Applied seasonal (HF, LF) and non-seasonal (all year) threshold levels

climatic region	station	Q_{90} all year (m^3/s)	Q_{70} all year (m^3/s)	Q_{70} LF (m^3/s)	Q_{70} HF (m^3/s)
Northern Zone	GUATUSO	7,3	14,0	7,9	23,4
Northern Zone	TERRÓN COLORADO	52,8	89,3	58,1	133,0
Northern Zone	CARIBLANCO	3,3	5,4	3,8	7,7
North Pacific	GUARDIA	6,2	10,2	6,7	14,2
North Pacific	RANCHO REY	3,9	5,3	4,3	7,3
Central Valley	GUAPINOL	2,2	3,5	2,4	7,4
Central Valley	TACARES	4,7	6,3	5,1	10,7
Central Pacific	EL REY	4,9	8,7	5,2	20,2
Central Pacific	LONDRES	5,8	12,0	5,8	25,6
Central Pacific	PROVIDENCIA	1,8	2,8	1,9	5,1
South Pacific	PALMAR	55,5	107,0	59,7	266,0
South Pacific	CARACUCHO	16,5	28,9	17,6	58,5
Caribbean	PALOMO	11,4	20,4	12,5	33,2
Caribbean	ORIENTE	10,2	17,3	11,1	26,6
Caribbean	DOS MONTANAS	18,1	32,1	20,0	47,3
Caribbean	PANDORA	13,1	20,7	15,8	27,0
Caribbean	BRATSI	62,2	101,0	84,4	143,0

Tab. 3.3 Complete statistics table (mean, S) for all stations and threshold levels applied

station	threshold	mean AMD	S	mean AMV	S	mean ND	S
Guatuso	Q_{90} annual	36	18	127	93	1,2	0,7
	Q_{70} annual	89	31	1540	621	2,4	1,1
	Q_{70} LF	41	21	194	138	1,3	0,8
	Q_{70} HF	20	10	368	293	2,7	1,6
Bratsi	Q_{90} annual	31	19	206	187	1,6	1,3
	Q_{70} annual	61	30	1342	823	3,9	1,6
	Q_{70} LF	50	27	681	515	2,8	1,4
	Q_{70} HF	18	15	364	404	2,3	1,7
Cariblanco	Q_{90} annual	26	22	155	185	1,5	1,2
	Q_{70} annual	73	37	1336	832	2,7	1,4
	Q_{70} LF	42	28	334	312	1,6	0,8
	Q_{70} HF	22	15	357	396	2,3	1,5
El Rey	Q_{90} annual	25	23	66	88	1,3	1,0
	Q_{70} annual	93	33	801	405	1,7	0,8
	Q_{70} LF	36	27	108	115	1,4	0,8
	Q_{70} HF	22	21	381	520	1,2	0,9
Guardía	Q_{90} annual	32	34	142	190	0,8	0,9
	Q_{70} annual	85	41	1041	767	2,2	1,2
	Q_{70} LF	39	36	220	258	1,0	0,8
	Q_{70} HF	18	19	181	204	1,7	1,6
Guapinol	Q_{90} annual	32	24	44	50	1,1	0,6
	Q_{70} annual	89	29	413	170	1,7	0,7
	Q_{70} LF	44	25	83	71	1,9	1,2
	Q_{70} HF	19	15	196	277	1,2	1,0
Dos Montanas	Q_{90} annual	25	25	156	185	1,6	1,3
	Q_{70} annual	63	33	1290	865	3,2	1,7
	Q_{70} LF	30	26	225	251	1,8	1,4
	Q_{70} HF	23	16	498	496	3,2	1,7
Pandora	Q_{90} annual	21	18	104	110	1,9	1,6
	Q_{70} annual	50	31	691	532	4,5	2,2
	Q_{70} LF	34	28	268	254	1,9	1,3
	Q_{70} HF	18	13	420	396	2,7	1,5
Oriente	Q_{90} annual	19	14	116	128	1,9	1,3
	Q_{70} annual	58	30	1126	698	3,7	2,0
	Q_{70} LF	26	18	183	180	2,0	1,0
	Q_{70} HF	20	10	509	400	2,8	1,5
Palomo	Q_{90} annual	22	16	126	131	1,8	1,3
	Q_{70} annual	67	30	1307	715	3,1	1,3
	Q_{70} LF	29	18	205	181	2,1	1,5
	Q_{70} HF	18	15	442	574	2,6	1,5
Caracucho	Q_{90} annual	26	24	94	124	1,6	1,1
	Q_{70} annual	97	27	1196	502	1,6	0,8
	Q_{70} LF	34	27	139	152	1,7	1,0
	Q_{70} HF	28	23	572	583	1,8	1,0
Palmar	Q_{90} annual	27	23	77	79	1,6	1,0
	Q_{70} annual	97	32	1159	459	1,5	0,7
	Q_{70} LF	32	24	112	105	1,7	1,0
	Q_{70} HF	25	21	578	640	1,6	1,3
Providencia	Q_{90} annual	25	26	103	195	1,2	1,2
	Q_{70} annual	95	45	982	657	2,0	1,1
	Q_{70} LF	35	30	136	214	1,3	1,2
	Q_{70} HF	20	24	316	467	0,6	0,6
Londres	Q_{90} annual	28	25	95	119	1,4	1,1
	Q_{70} annual	99	39	1562	753	1,4	0,7
	Q_{70} LF	**Q90 annual**					
	Q_{70} HF	15	18	275	369	1,2	1,0
Tacares	Q_{90} annual	27	30	133	188	1,2	1,2
	Q_{70} annual	90	46	985	697	1,8	1,0
	Q_{70} LF	43	35	253	295	1,3	0,8
	Q_{70} HF	23	24	384	565	1,0	0,7
Rancho Rey	Q_{90} annual	28	35	178	270	1,1	1,2
	Q_{70} annual	74	52	958	888	2,9	2,4
	Q_{70} LF	43	41	344	426	1,2	1,1
	Q_{70} HF	17	20	279	498	1,8	1,8
Terrón Colorado	Q_{90} annual	28	25	149	179	1,5	1,1
	Q_{70} annual	69	33	1239	748	2,7	1,2
	Q_{70} LF	35	27	260	254	1,6	1,1
	Q_{70} HF	17	12	328	380	2,0	1,3

Tab. 4.4 Seasonally (LF, HF) anomaly indices (D) for the ACD period 1991-1995 of all stations

D	ACD LF					ACD HF				
station	**1991**	**1992**	**1993**	**1994**	**1995**	**1991**	**1992**	**1993**	**1994**	**1995**
Guapinol	0,21	1,33	0,71	1,67	0,08	-0,05	-0,35	-0,30	0,50	0,25
El Rey	-0,43	1,18	-0,36	1,50	-0,93	1,68	0,08	-0,24	-0,48	-1,08
Guardia	1,15	1,40	1,18	1,03	1,25	1,94	2,09	-0,14	1,43	0,00
Guatuso	0,44	1,00	1,26	1,22	0,41	-0,18	-0,55	-1,36	-0,18	-0,23
Londres	-0,67	0,48	-0,11	1,07	-0,37	-0,14	-0,67	1,71	-0,14	-0,29
Oriente	0,07	0,15	-0,26	1,78	-0,37	0,55	1,20	0,90	1,10	0,45
Palmar	0,00	1,48	-0,15	1,52	0,70	1,26	1,89	0,19	1,44	-1,26
Palomo	0,14	1,39	-0,43	0,43	1,14	1,38	2,17	0,17	0,29	1,79
Pandora	0,52	-0,68	1,65	0,97	-1,45	0,38	-0,79	0,04	-0,17	0,00
Providencia	0,65	1,30	0,70	1,75	0,70	-0,88	-0,88	0,08	-0,88	-0,88
Rancho Rey	0,44	2,15	0,69	1,35	0,69	0,94	0,89	0,09	0,60	-0,86
Tacares	-0,76	1,19	-0,22	0,97	1,35	1,24	1,20	-0,44	-1,04	-0,48
Terrón Col	0,65	0,32	0,48	2,61	0,48	-0,74	0,91	0,61	0,17	-0,61
Bratsi	0,29	0,75	-1,19	0,84	0,49	0,98	0,04	0,87	-0,15	-0,35
Caracucho	-0,07	2,71	0,00	0,61	-1,18	1,11	2,30	-0,30	0,59	-0,41
Cariblanco	0,78	1,31	-1,38	1,44	1,84	-0,07	0,90	-0,07	-0,21	0,66
Dos Montanas	-0,29	0,74	-0,71	1,45	0,71	-0,08	1,05	4,23	-0,03	0,62
µ:	0,18	1,07	0,11	1,31	0,33	0,55	0,68	0,35	0,17	-0,16
S:	0,50	0,75	0,82	0,50	0,89	0,82	1,05	1,16	0,69	0,73

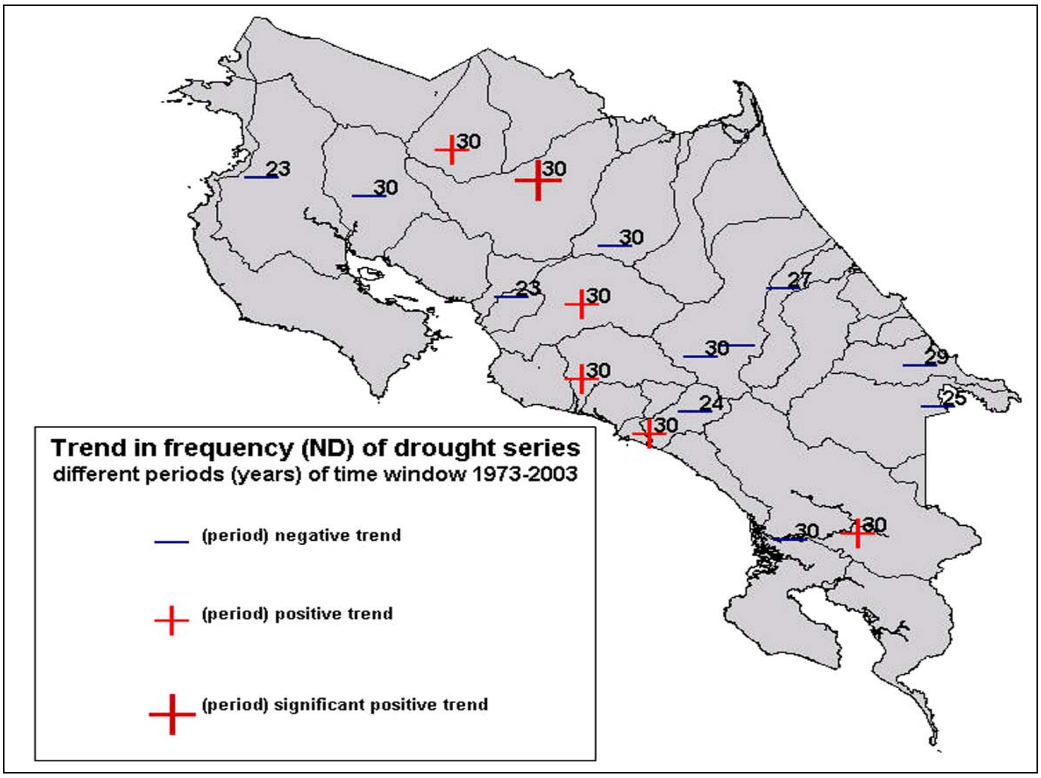

Fig. 4.16 Trend in frequency (ND) of drought series for the period 1973-2003

Tab. 5.8 Complete correlation table (1973-2003) for all stations between seasonal SST's and seasonal (HF, LF) anomaly indices (ACD, ACV)

station	r (SST3.0-LF ACD)	r (SST3.0-LF ACV)	r (SST3.0-HF ACD)	r (SST3.0-HF ACV)
Guapinol	0,03	0,06	0,70	0,44
El Rey	0,31	0,24	0,49	0,50
Guardia	0,42	0,40	0,33	0,31
Guatuso	0,39	0,43	0,03	0,10
Londres	0,22	-0,03	0,57	0,44
Oriente	0,50	0,54	0,20	0,16
Palmar	0,27	0,28	0,50	0,46
Palomo	0,60	0,79	0,39	0,26
Pandora	-0,07	-0,07	0,14	-0,39
Providencia	0,24	0,01	0,31	0,27
Rancho Rey	0,22	0,23	0,34	0,22
Tacares	0,29	0,28	0,04	0,03
Terrón Col	0,20	0,16	0,23	0,43
Bratsi	0,26	-0,08	-0,01	-0,06
Caracucho	0,39	0,42	0,60	0,57
Cariblanco	0,12	0,00	-0,27	-0,11
Dos Montanas	0,32	0,28	0,17	0,12

Ehrenwörtliche Erklärung:

Hiermit erkläre ich, daß die Arbeit selbständig und nur unter Verwendung der angegebenen Hilfsmittel angefertigt wurde.

Ort, Datum Unterschrift