UNIVERSIDAD AUTÓNOMA DE SAN LUIS POTOSÍ
FACULTADES DE CIENCIAS QUÍMICAS, INGENIERÍA Y MEDICINA
PROGRAMAS MULTIDISCIPLINARIOS DE POSGRADO EN CIENCIAS AMBIENTALES
AND
TH KÖLN - UNIVERSITY OF APPLIED SCIENCES
INSTITUTE FOR TECHNOLOGY AND RESOURCES MANAGEMENT IN THE TROPICS AND SUBTROPICS

HYDROLOGICAL DROUGHT ASSESSMENT IN THE TEMPISQUE-BEBEDERO CATCHMENT SYSTEM IN COSTA RICA

THESIS TO OBTAIN THE DEGREE OF
MAESTRÍA EN CIENCIAS AMBIENTALES
DEGREE AWARDED BY UNIVERSIDAD AUTÓNOMA DE SAN LUIS POTOSÍ
AND
MASTER OF SCIENCE
NATURAL RESOURCES MANAGEMENT AND DEVELOPMENT
DEGREE AWARDED BY TH KÖLN – UNIVERSITY OF APPLIED SCIENCES

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COLOGNE, GERMANY DATE 28.08.2017

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Universidad Autónoma de San Luis Potosí
Facultades De Ciencias Químicas, Ingeniería Y Medicina
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LA MAESTRÍA EN CIENCIAS AMBIENTALES RECIBE APOYO A TRAVÉS DEL PROGRAMA NACIONAL DE POSGRADOS

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Erklärung / *Declaración*

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To my beloved nephews Valeria and Nicolás

"Lo más terrible se aprende enseguida, y lo hermoso nos cuesta la vida." S.R

Abstract

The present thesis research was focused on the assessment of hydrological drought in the Tempisque-Bebedero catchment system in Costa Rica as part of the TropiSeca project framework. The study area is in the province of Guanacaste and has an extension of 5449.94 Km^2, the region is characterized by a defined wet and dry season resulting in a marked seasonality in precipitation and streamflow regime which provokes frequent periods of water deficits considered as drought.

The main objective of this research is to conduct an analysis on hydrological drought in the study area through the understanding of the behavior of hydrological cycle and its implications for the rice sector by applying different drought indices such as Standardized Precipitation Index (SPI) and Streamflow Drought Index (SDI). From the values obtained in the calculation of drought indices were studied the temporal distribution and spatial distribution based on the characterization of drought periods in terms of frequency, severity, duration, and seasonality.

For the characterization of meteorological drought in the study area an approach based on area average precipitation was implemented to calculate a regional representative SPI for each sub-basin, in contrast, hydrological drought was assessed using only two streamflow gauges data provided by the ICE from 1973 until 2003.

As result, Tempisque showed longer drought periods in comparison with Bebedero whose mean duration was lower but the number of drought events were more frequent. In terms of spatial distribution, it could be found that the upper basin experienced extreme meteorological drought periods at high time scales tied to a severe streamflow deficit probably justified by its low permeability due to geological characteristics that allow a slow movement of groundwater.

Additionally, one of the aims of this thesis was to analyze the existence of correlation between precipitation and streamflow anomalies with rice yield and, to determine the influence of ENSO in climate variability using Sea Surface Temperature indices; in this phase of the research was found that climate patterns in the catchment system exhibited a significant influence by ENSO events with a significance level of 99% ($r > 0.7$) showing an important dependence of meteorological drought periods presented during the period 1980-2016.

In terms of temporal behavior of rice yield anomalies was revealed moderate correlation coefficients ($r < 0.4$) in both watersheds due to in most of the cases the response of water deficit did not have significant impact in terms of magnitude as expected; in some periods in which drought period was present categorized as mild-drought, rice yield had a considerable decreasing compared with those in which was categorized as extreme event; these differences can be justified mostly because crop yield depends not only on weather, but also on variety of seed used and its coping capacity to periods of water scarcity, fertilizers, soil moisture, farming techniques, sowing date, temperature, irrigation, use of pesticides etc.

The results of this thesis can be used to motivate future researches in the elaboration of crop models to predict yields based on physiological processes during plant development considering water requirement to take enough measures to mitigate the effects of drought periods. Furthermore, it should be considered to implement a drought monitor system in the area as an important tool of early warning system and as an indicator for the efficient water resources management.

Key words: Drought, SPI, SDI, ENSO, Rice yield, El Niño, Climate, Tempisque, Bebedero, Costa Rica, Correlation, Spatial distribution, Temporal distribution.

Abbreviations

CHIRPS: Climate Hazards Group InfraRed Precipitation with Station data

CONARROZ: Corporación Arrocera Nacional

CPC: Climate Prediction Center

ENSO: El Niño–Southern Oscillation

FDC: Flow Duration Curve

ICE: Instituto Costarricense de Electricidad

ITCZ: Intertropical Convergence Zone

IDW: Inverse Distance Weighting method

INEC: Instituto Nacional de Estadística y Censos

INS: Instituto Nacional de Seguros

MDS: Mild-summer drought

MAG: Ministry of Agriculture and Livestock

MINAE: Ministerio de Ambiente y Energía de Costa Rica

NCEP: National Centers for Environmental Prediction

NOAA: National Oceanic & Atmospheric Administration

PET: Potential Evapotranspiration

SDI: Streamflow drought index

SEPSA: Secretaría Ejecutiva de Planificación Sectorial Agropecuaria

SOI: The Southern Oscillation Index

SPI: Standardized Precipitation Index

SPI_{RT}: Standardized Precipitation Index- (Regional Tempisque)

SPI_{RB}: Standardized Precipitation Index-(Regional Bebedero)

SST: Sea Surface Temperature

STI: Standardized Temperature Index

THLM: Threshold Level Method

UNISDR: The United Nations Office for Disaster and Risk Reduction

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1. INTRODUCTION

The increasing occurrence of droughts has been a concern around the world especially in the context of climate change caused by anthropogenic activities, as these alter the hydrologic cycle causing several alterations to the environment and generating social and economic impacts.

Climate plays an important role in this context because the temperature of the planet has been increasing in tropic areas, increasing natural hazards such as droughts. According to IPCC (2013) the effects of steadily rising concentrations of greenhouse gases in the climate may be less obvious to tropical residents, however, because they are overlain by considerable natural variability.

During the last century, temperature increased in the tropics by 0.7-0.8 °C. El Niño phenomenon made 1997-1998 the warmest period in most areas, with no significant warming since. Climate models predict a further warming of 1-2 °C by 2050 and 1-4 °C by 2100, but the rise will certainly not be as smooth as the graphs that are produced by averaging many different climate models (Corlett, 2014).

The study of this variability and its implications have attracted a great interest in different sectors through management programs to understand and mitigate the effects of natural hazards. These hazards cause economic, social and environmental problems which can only be controlled by new policies and economic inversion in the prevention and control of droughts effects on environment, water supply and food security, among others. Most drought-related hazards and the attendant economic losses and mortality risks reside in the tropics (Dilley et al. 2005). Changes in climate variability, including more frequent and damaging extreme events such as drought, is one of many anticipated impacts of climate change (Coelho & Goddard, 2009, p. 6456).

According to the above, this research thesis was developed in the Tempisque-Bebedero catchment as study area, which is in Costa Rica, specifically in the Guanacaste province. As reported by the National Meteorological Institute (2016), this area is prone to drought periods, some of them are associated with El Niño–Southern Oscillation events. However, not all the drought events presented in the area are linked to this phenomenon; it is a fact that their consequences affect not only the community but also the environment in terms of water supply, soil properties, vegetation condition, agriculture and food security.

1.1. Justification

Climate change has been studied for many years thereby indicating that the variability and extreme events are increasing constantly and that they are related to anthropogenic causes. According to the Intergovernmental Panel on Climate Change report (2007) the temperature during 1910 and 1940 increased in 0,35 °C, but the greatest temperature was registered from the 1970s to the present in 0,55 °C. An increasing rate of warming has taken place over the last 25 years, and 11 of the 12 warmest years on record have occurred in the past 12 years (Ashok, M., & Vijay, S., 2010), these events bring as result droughts in tropical and subtropical areas causing several damages to the ecosystem, biodiversity, soil properties, and water supply, so forth.

Regardless the existence of many different types of drought according to the literature, in this research considered the comprehension of meteorological and hydrological drought and their possible impacts on rice agriculture, as it results crucial for future studies regarding mitigation of the effects in terms of food security, water supply for irrigation and productivity.

This research project was conducted in Costa Rica in the Tempisque-Bebedero catchment system as part of one of the study areas of the TropiSeca project scope focused on hydrological drought. The project aims to promote effective strategies for water management under scarcity conditions, for this reason, the prediction and mitigation of drought impacts is important to understand hydro-climatological processes.

As part of comprehension of hydrological drought, it is important to distinguish its main impacts, thus, an analysis based on statistical approaches was undertaken to understand possible trends and correlations between precipitation and streamflow anomalies by the calculation of drought indices such as the standardized precipitation index (SPI) and the streamflow drought index (SDI). Furthermore, the influence of ENSO phenomenon on climate variability and their possible implications on temporal rice yield anomalies were analyzed

1.2. Objectives

General objective

- To conduct an analysis on hydrological drought of the Tempisque-Bebedero catchment in Costa Rica and its implications in the rice sector.

Specific objectives

- To identify major droughts, their severity, and seasonality using indicators for meteorological and hydrological drought at different temporal scales in the Tempisque-Bebedero catchment.

- To explore the propagation of drought through the hydrological cycle based on the development of the standardized precipitation index (SPI) and Streamflow drought index (SDI) and their significance on rice yield temporal behavior.

- To determine the influence of ENSO phenomena on climate variability patterns and their effect on drought periods in terms of severity and duration.

- To analyze the existing correlation among rice crop yield, SPI, Temperature anomalies and SST indices based on temporal and spatial distribution at different time scales for the period 2004-2016.

2. THEORETICAL FRAMEWORK

2.1. What is drought?

Due to drought is a recurring phenomenon, there is not a specific definition for this concept, for this reason it is possible to find several attempts from different authors and study fields to define or understand what it is and the variables by which it can be explained. However, what it is well known about this natural hazard is how much it has affected different sectors throughout the development of civilizations. This wide variety of sectors affected by drought, its diverse geographical and temporal distribution, and the demand placed on water supply by human-use systems make it difficult to develop a single definition of drought (Heim, 2002).

Nevertheless, droughts are understood by most of the authors as a precipitation and streamflow deficit relative to average conditions, or in terms of water balance indices (Hisdal & Tallaksen, 2003, p. 231). According to this, it can be established that droughts are a perturbation in the natural climatic and hydrologic regime which can affect the determinants of water quality in multiple ways. For example, low flows and water levels observed during hydrological droughts increase the residence time and reduce the flushing rate of water bodies. Reduced water flows/levels and elevated temperatures during some droughts may change the rates of processes such as productivity, respiration (Mosley, 2015, p. 204). Therefore, drought cannot be compared with another natural hazard such floods or cyclones because the effects of droughts accumulate their effects slowly over a considerable period of time and may linger for years after the termination of the event, the onset and end of drought is difficult to determine (Wilhite, 2000).

2.2. Impacts of drought

During droughts, the climate water deficit propagates through the hydrological cycle and can subsequently reduce groundwater levels, streamflow, and lake levels (Mosley, 2015, p. 204).

Figure 1 shows the main impacts in different sectors generated by droughts.

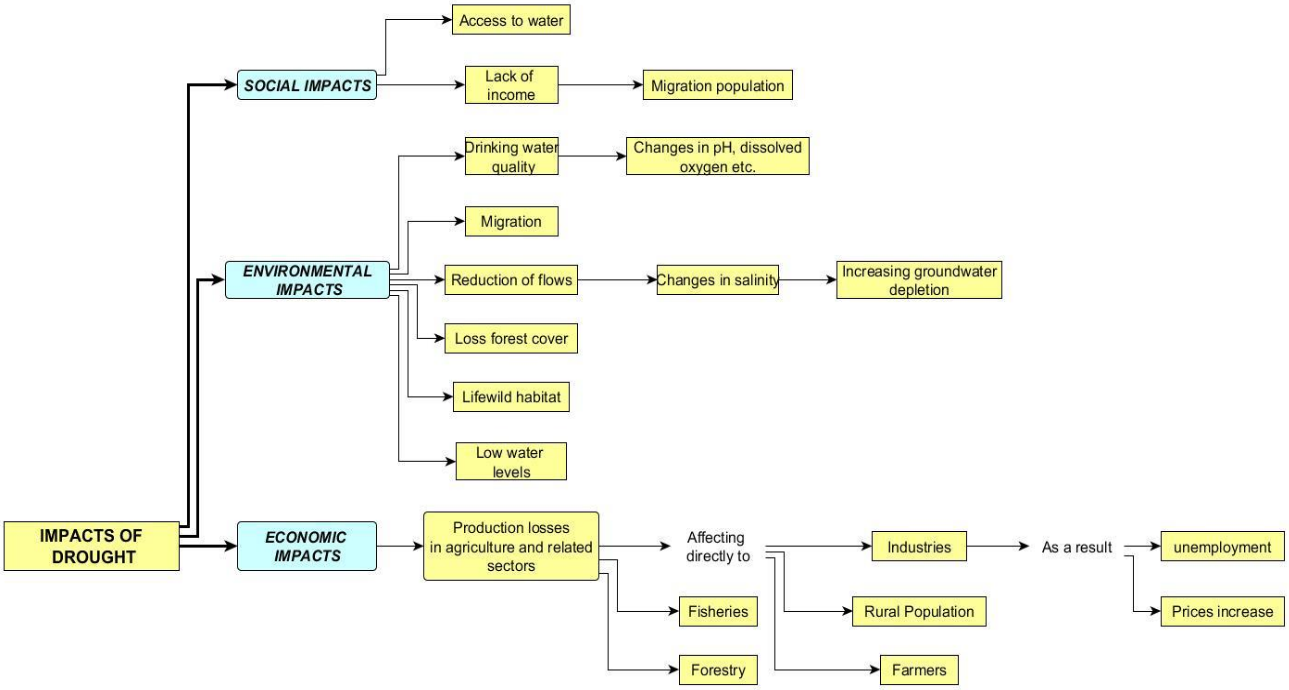

Figure 1 Impacts of drought in different sectors
Elaborated by the author based on: (Ministry of Agriculture, 2009)

2.3. Types of droughts

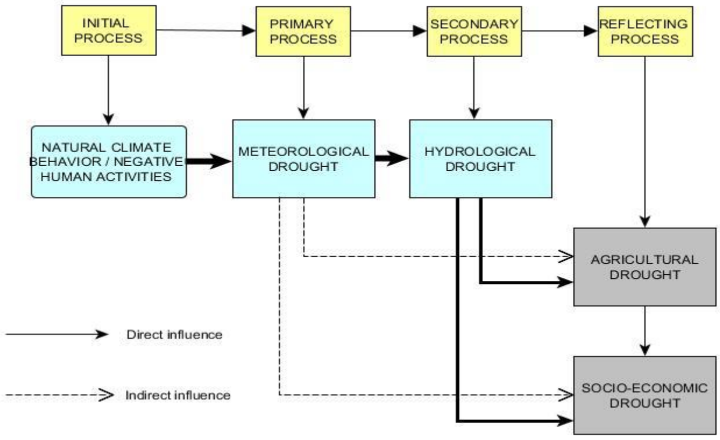

Figure 2 Types of droughts
Source: (Manoj Khanna, 2009)

The discussion of the disciplinary perspectives of drought which follows is the result of a review of more than 150 published definitions. For purposes of discussion, these definitions of drought are clustered into four types: meteorological, agricultural, hydrologic, and socio-economic (Figure 2) (Wilhite & Glantz, 2009).

Sometimes the origin of droughts can be associated to negative human actions; however, it is important to clarify that variability on precipitation is a normal behavior of climate called

Meteorological drought, which is defined as a deficit in precipitation. This type of drought can further develop into a hydrological drought understood as a shortfall in surface water and groundwater level. These types of droughts can promote the developing of agricultural drought as a reflecting process, thereby affecting the food production and causing socio economic impacts.

“The choice of a suitable drought characteristic for a specific study depends on the hydro-climatology of the region, the type of drought considered, the vulnerability of society and nature in that region, the purpose of the study and the available data. Due to the lack of a unique standard definition, this choice is subjective and a large number of different characteristics are used to describe and quantify droughts” (Fleig, Tallaksen, Hisdal, & Demuth, 2006, p. 536).

2.4. Drought Indices

According to the literature, there are different types of drought and several ways to study their characteristics by using specific indices applying a certain number of indicators linked to available data and feasibility of research. This study case, is focused on Hydrological drought assessment by the analysis of the effects of precipitation shortfall on streamflow and, the effect on rice agriculture.

Droughts can be characterized in three dimensions: severity, duration and spatial distribution, however, extra characteristics can be listed to complement them, such as severity, magnitude, frequency, seasonality etc. (Zargar, Sadiq, Naser, & Khan, 2011).

2.5. Drought characterization

The use of indicators is one of the most important tools in the field of drought research, thus, the implementation of different types of indices by assimilating indicators into a single numerical value is considered an important issue to study each dimension of drought for monitoring, forecasting and planning based on results.

Drought indices are classified according to the effect that they produce on the environment and so on, being Meteorological, Hydrological and Agricultural drought the most used. However, iemeye (2008) has proposed to add three new categories to the list: Comprehensive, combined and remote-sensing-based drought indices. Comprehensive drought indices use a variety of meteorological, agricultural and hydrological variables to draw a comprehensive picture of drought. The Palmer Drought Severity Index (PDSI) is an example of this approach. Remote-sensing-based drought indices use information from remote-sensing sensors to map the condition of the land (e.g., the Normalized Difference Vegetation Index, NDVI, (Tucker, 1979). Combined (also termed hybrid and aggregate) drought indices are derived by incorporating existing drought indicators and indices into a single measure (Zargar et al., 2011).

2.5.1. Standardized Precipitation Index (SPI)

The SPI index was developed by McKee, Doesken, & Kleist (1993) based on monthly precipitation data. This index compares precipitation with the average value for multiple timescales in a normal distribution. Values below zero indicate dry periods. For any given drought, its score in SPI represents the number of standard deviations its cumulative precipitation deficit deviates from the normalized average (Drought Watch, 2010). The authors of this index, propose to calculate the SPI at different monthly periods 1, 3, 6, 9 and 12 depending on the application (Table 1)

Table 1 Phenomena reflected by specific-duration standardized precipitation indices (SPI) and their applications

SPI duration	Phenomena reflected	Application
1-month SPI	Short-term conditions	Short-term soil moisture and crop stress (especially during the growing season)
3-month SPI	Short- and medium-term moisture conditions	A seasonal estimation of precipitation
6-month SPI	Medium-term trends in precipitation	Potential for effectively showing the precipitation over distinct seasons. e.g., for California, the 6-month SPI can effectively indicate of the amount of precipitation from Oct. to Mar.
9-month SPI	Precipitation patterns over a medium time scale	If SPI 9 < –1.5 then it is a good indication that substantial impacts can occur in agriculture (and possibly other sectors)
12-month SPI	Long-term precipitation patterns	Possibly tied to streamflows, reservoir levels, and also groundwater levels

(National Drought Mitigation Center, 2006)

Many authors have established to use for this index at least 30 years of recorded data of precipitation, however studies by different authors as cited in Wanders, van A.J Lanen, & van Loon (2010, p. 29) used shorter periods of 30 years.

2.5.2. Streamflow Drought index (SDI)

The Standardized Streamflow Index (SDI) is based on the same concept as the SPI. The SDI has been newly developed and uses a normalized gamma distribution for the daily discharge. The SDI is classified as a hydrological drought indicator. The only variable taken into account, is the water discharge (Wanders et al., 2010). For the development of Standardized Streamflow Index (SDI), it is important to find available information of a time series of monthly streamflow volumes in the watershed of study.

3. STUDY AREA

3.1. Tempisque-Bebedero catchment system

3.1.1. Location

The Tempisque-Bebedero catchment system is in the province of Guanacaste (Figure 4) and is one of the most important in the country due to its extension. The system is formed by two main watersheds, Tempisque and Bebedero, which are a source for agricultural irrigation, hydroelectrical production and drinking water supply to the community of the 11 municipalities of the province. The waters of the Tempisque River originate in the volcanic sierra of Guanacaste and flow 144 km before they reach the Gulf of Nicoya, which also forms part of the area of influence of the watershed. The river itself extends over 108 km and it has an area of 5465 km2. (Jimėnez-Romȧn, Gonzȧlez-Jimėnez, & Mateo-Vega, 2001).

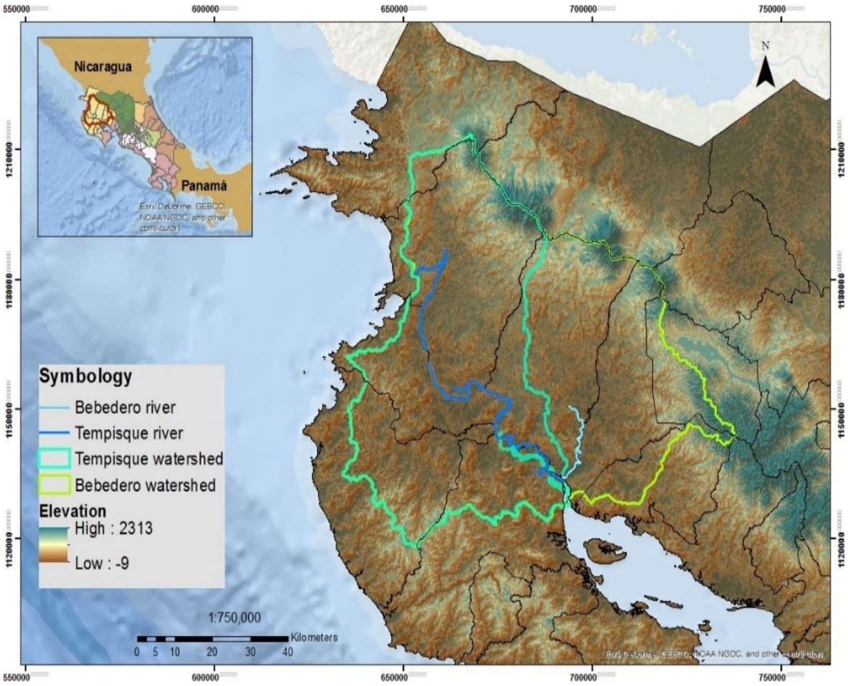

Figure 3 Location of Tempisque Basin
Elaborated by the author based on: (Ortiz 2014)

3.2. Climate

Central America and as a part of it Costa Rica, is characterized 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 (Birkel, July/2005, p. 21).

Droughts in Costa Rica are frequent in the Pacific North Region due to the low precipitation rate which it is below of 1500 mm on average. According to this, places which are located northward are suitable to study because they are more prone to drought events.

3.2.1. Mean precipitation

The rainfall distribution in the catchment system varies in average from 2850 mm in the lower basin, 1900 in the middle basin and 1600 mm in the upper area (Figure 4). The driest months are among January, February and march, and the rainiest are between September and October (Figure 5) according to IMN reports obtained for a period from 1948 to 2016 in different gauging stations in the study area.

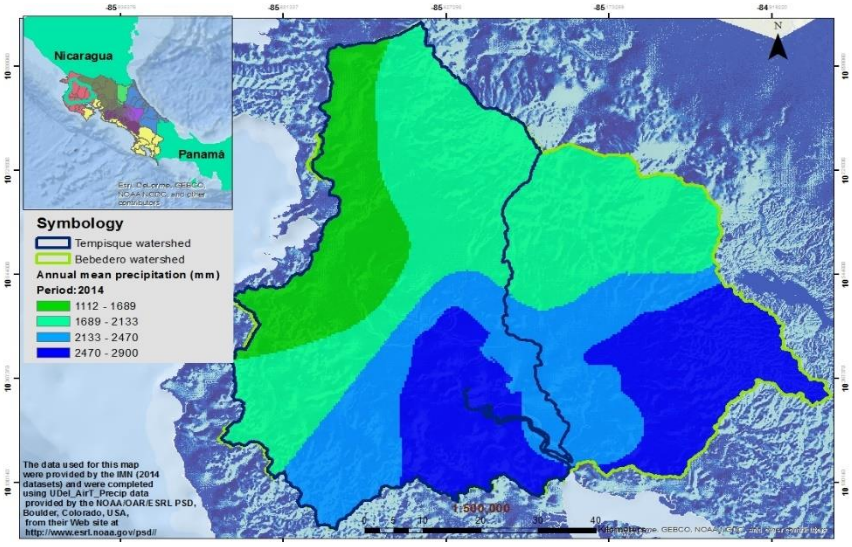

Figure 4 Annual mean precipitation in Tempisque-Bebedero catchment system
Elaborated by the author based on: (IMN, 1948-2016; Matsuura & Willmott, 1900-2014)

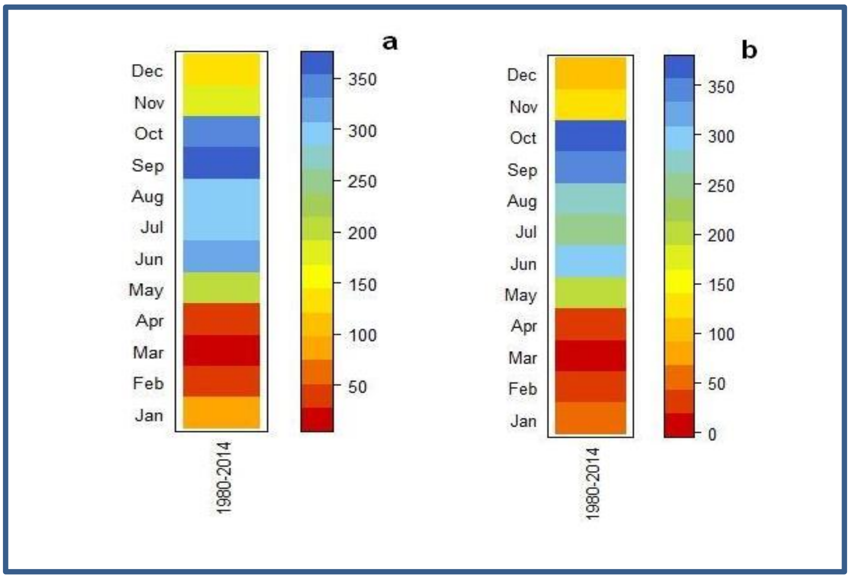

Figure 5 Monthly rainfall distribution in a) Bebedero and b) Tempisque
Elaborated by the author based on: (IMN, 1948-2016)

3.2.2. Mean Temperature

In the figure 6 is represented the isothermal map for the study area in which can be appreciated the variation in the mean temperature according to the altitudinal gradient, showing a value approximately of 28 °C in the lower areas and values ≤ 21 °C in zones with a higher elevation.

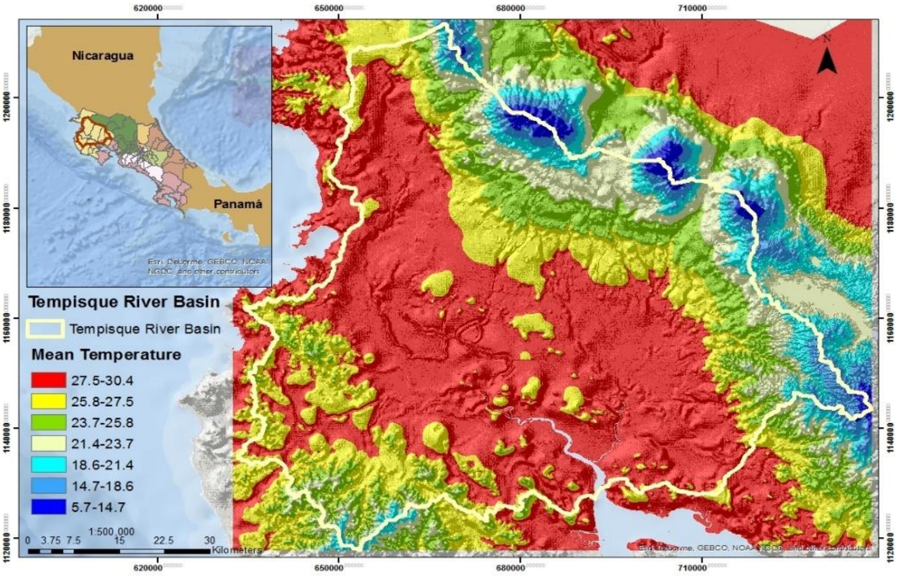

Figure 6 Annual mean temperature in Tempisque-Bebdero catchment system
Elaborated by the author based on: (Ortiz, 2014)

3.2.3. Mean evapotranspiration

According to Bolaños, Echeverria, & Losilla (1998) the annual potential evapotranspiration is around 1989 mm, but other authors such as Vaughan et al. (1996), determined that can be 2100 mm per year in the low-basin of the Tempisque Basin; it means that the PET (Potential evapotranspiration) is higher than the annual precipitation in the zone, for that reason this area is prone to drought events with very strong water shortfalls (table 2).

Table 2 Surface Water Balance in Tempisque-Bebedero catchment system

Sub-Basin	**Area**	**Precipitation**		**Runoff**		**Real evapotranspiration**	
	km^2	**mm**	**km^3**	**mm**	**km^3**	**mm**	**km^3**
Tempisque	3369,68	1833	6,25	712	2,43	1002	3,42
Bebedero	2080,26	1776	3,65	910	1,87	1087	2,23

Source: (Berrantes, 2006)

3.3. Hydrology-Hydrogeological aspects

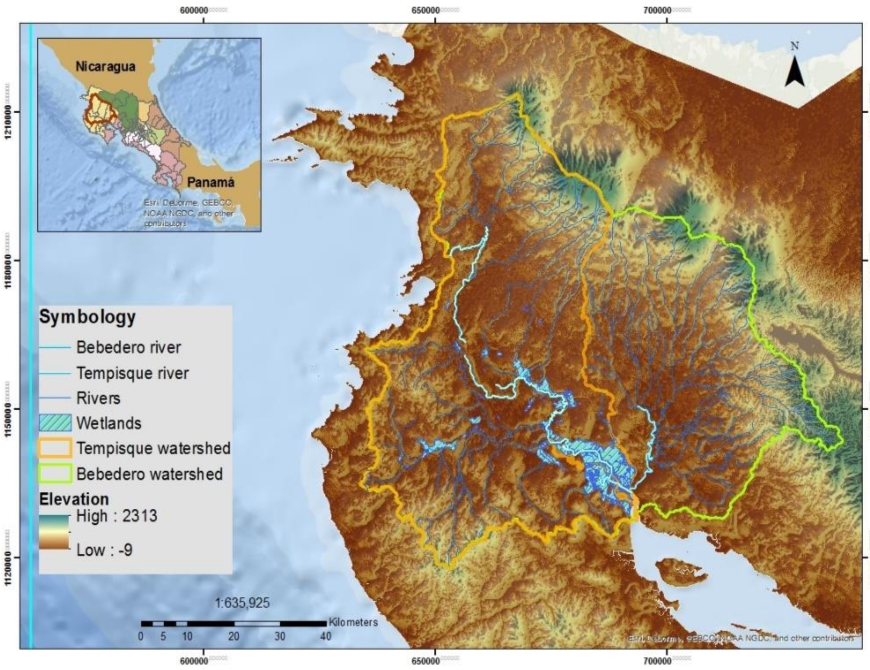

Figure 7Hydrology in Tempisque-Bebedero catchment system
Elaborated by the author based on: (Ortiz, 2014)

The catchment system is formed by two watersheds: Bebedero and Tempisque, both are important fluvial systems in Guanacaste for agriculture, livestock, and human consumption, tourism and Hydropower purposes. The Basin contains a big hydrological net which crosses the municipalities of Liberia, Santa Cruz, Bagaces, Cañas and Tilarán. The main channels that form part of the basin can be observed in the map (Figure 7).

Guanacaste has different types of rock formations as it was shown in Table 4. These geologic formations are responsible of the aquifers formed and their storage potential. Due to these rock types with a high and low hydrologic potential some wells were formed that constitute an important part in terms of water storage for the province mainly in periods of scarcity.

The most relevant aquifers located in the basin are formed by volcanic and Hypoabisals rocks such as Bagaces and Liberia aquifers (table 3), both are in volcanic rocks, with the difference that the first one is contained in fractured lava while the second is formed by explosive rocks (Ignimbrites and / or tuffs) (MINAE, 2008, p. 4).

Table 3 Aquifers in Tempisque-Bebedero catchment system

Aquifer	Characteristics	Studied by
Bagaces	The recharge of this aquifer is given by direct infiltration of rain across the Santa Rosa Plateau. **Upper section**: It has a mean streamflow of 3.78 L/s, it is formed by pink and gray tuff. Clear brown tuffs[1] with well cemented fragments. They have a low permeability (average thickness is 30 m). This hydrogeological feature allows a slow movement of groundwater **Middle section:** It has a mean streamflow of 189 L/s; it is formed by hard and brown tuffs. Good permeability (average thickness is 200 m). **Lower section:** It is formed by a columnar gray tuff (clay-loam) Low permeability determines a certain connection with the alluviums of the valley of the Tempisque	(Naciones Unidas, 1975; Yoshida & Pérez, 2000)
Liberia	Due to it is formed mainly by clay material; its permeability is quite low. The infiltration depends on the amount and duration of rainfall. It has an extension of 432 km^2 with a flat topography.	(Naciones Unidas, 1975)
Tempisque	Many studies have divided the Tempisque in two sections: Left and right; the left section is formed by fine materials, known as impermeable and impermeable deposits, the right site is opposite. The right section was divided by the National Service of Ground Water, Irrigation and Drainage (SENARA) in 5 study zones for agricultural purposes according to its hydrogeological potential.	(JICA, 2002)
Bebedero	It is formed by an alluvial deposit of materials carried by the rivers Bebedero, Cañas, Corobicí, Piedras and Tenorio, this aquifer is located between of Bebedero and Cañas municipalities and goes until the intersection with the river Tempisque. The static level is between 3 and 7 meters deep and the thicknesses vary between 8 to 20 m	. (MINAE, 2008, p. 9)

1. *Tuffs are pyroclastic rocks formed from volcanic material*.

Source: (MINAE, 2008)

3.4. Geology

The study area presents different geologic classifications in each area of the basin. Among its most important formations are described in table 4.

Table 4 Geological classification of the Tempisque-Bebedero catchment system

Eon	Era	Period		Epoch	Million Years ago	Formation
Phanerozoic	Cenozoic	Quaternary		Holocene	0,01	Formation of Tenorio and Miravalles Volcanoes piedmont- (Qv2). Presence of sedimentary rocks. The Tempisque depression (includes parts of the Gulf of Nicoya) (Qal)- formed by the fluvial, alluvial and coastal deposits The lower section of Tempisque is (Qa)-formed by an extensive area of wetlands.
				Pleistocene	2,59	Formation of volcanic and pyroclastic rocks in the north of the basin The Liberia and Bagaces formations (Qv2) (Qv1) found mostly along the Inter-American. Shallow marine formation
		tertiary	Neogene	Pliocene	5,3	Shallow Marine Deposits-sedimentary rocks formed.
				Miocene	23,03	Aguacate Complex (Tva) formed. (Upper Miocene)
			Paleogene	Oligocene	33,9	Sedimentary rocks of continental slope formed
				Eocene	55,8	Continental slope formed. Barra Honda and Brito (Tep) located in the right margin of the Tempisque is formed.
				Paleocene	65,5	Continental platform formed.
	Mesozoic	Cretaceous		Late	99	Nicoya complex (Kvs) formation of intrusive and marine sedimentary rocks
				Early	145	Intrusive rocks formation. The Sabana Grande (k) is formed in the lower areas of the basin

	Jurassic	Late	159	Deep marine sedimentary rocks are formed
		Middle	180	
		Early	206	
	Triassic	Late	227	
		Middle	242	
		Early	248	

Elaborated by the author based on: (Jiménez-Román et al., 2001; Rojas Nazareth, 2011)

3.5. Soil types

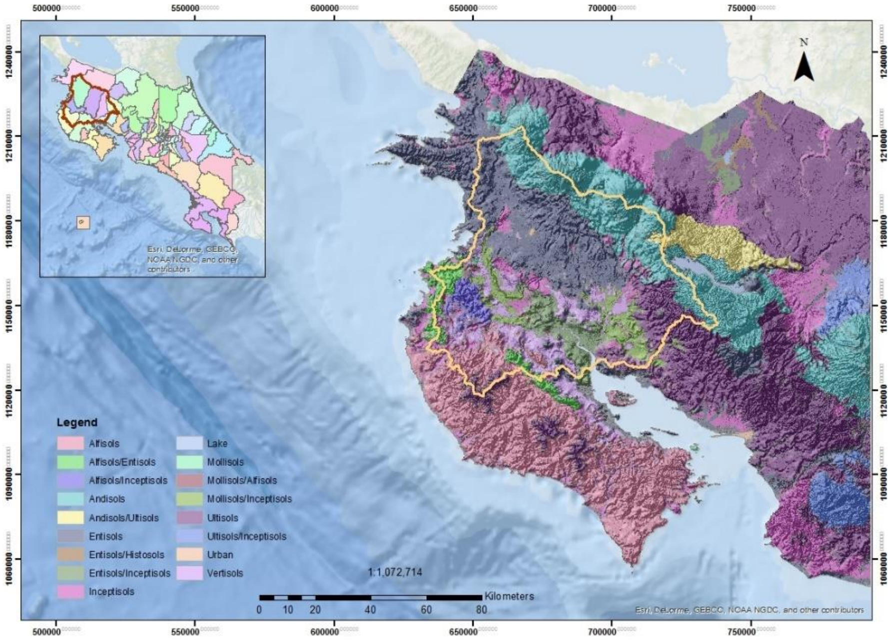

Figure 8 Soil orders
Elaborated by the author based on: (Mata & Sandoval, 2016)

The basin is formed by different soil orders among them: entisols, alfisols, inceptisols and andisols; which means that the study area has a wide edaphological diversity with different properties for different uses.

In figure 8 is shown the distribution of soils orders presented in the area.

3.6. Land cover

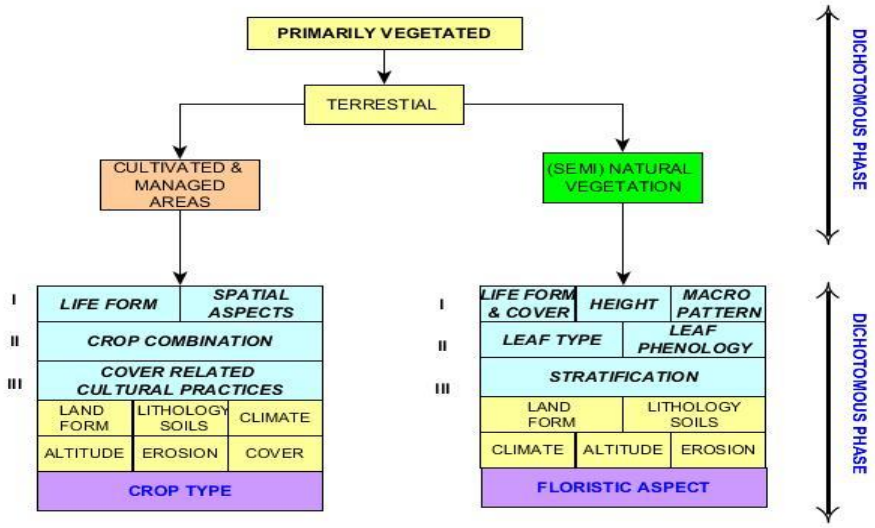

Figure 9 Land cover classification
Source: (Di Gregorio & Jansen, 2000)

The land cover is one of the most important characteristics in the study area as long part of this research is focused in the agricultural sector; however, not only crops are part of the general coverage in the region, inside of the Tempisque-Bebedero catchment system, there are many natural parks and protected areas that are affected by water scarcity periods and these consequences are reflected in their greenness and primary productivity.

To understand more about the divisions presented in terms of land cover, this research will settle in the definition proposed by the FAO as observed biophysical cover on the earth surface. Summing up, land cover according to Di Gregorio & Jansen (2000).

can be grouped into two main classes using a basic principle of hierarchical arrangement by the combinations of sets of classifiers divided by three dichotomous phases and various modular phases as shown in Figure 9.

3.6.1. Primarily vegetated: Terrestrial-Natural vegetation

The area is covered by different types of life zones according to its topography and climate conditions. The most remarkable zones are described in Table 5 showing the type of vegetation that can be found in each section of the Basin (Figure 10).

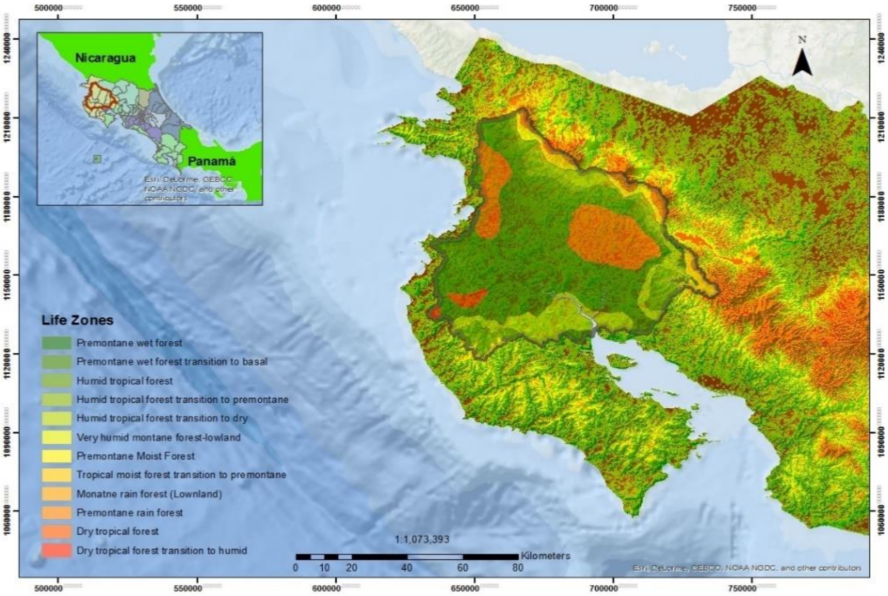

Figure 10 Life zones in the Tempisque-Bebedero catchment system
Elaborated by the author based on: (Ortiz, 2014)

Table 5. Life zones in the Tempisque-Bebedero catchment system

PART OF THE BASIN	TYPE OF VEGETATION
Upper Basin	In this area near Volcán Rincón de la Vieja predominates vegetation of montane rain forest type. As gradually the elevation decreases it becomes mountain rain forest.
Middle Basin	75% of the lower part of the basin is covered by vegetation classified as humid montane. 25% is covered by dry tropical forest with a transition into humid tropical forest and this last one with a transition to dry forest.
Lower Basin	In the litoral area of the river mouth of Tempisque basin in the Gulf of Nicoya, the vegetation is classified as wet montane forest.

(Rojas Nazareth, 2011)

❖ Floristic aspect: Protected areas

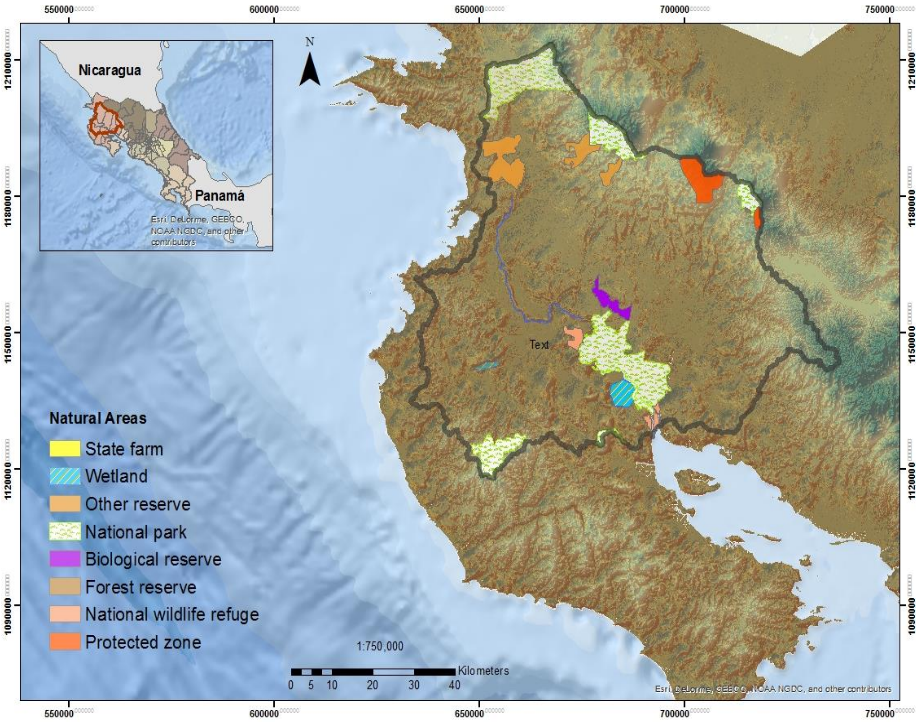

Figure 11 Natural Areas the Tempisque-Bebedero catchment system
Elaborated by the author based on: (Ortiz, 2014)

In the Guanacaste province there are important natural areas grouped into five classes according to their management category established by the SINAC (National system of conservation areas), these areas belong to the Tempisque conservation which extension is around of 552.000 ha (ACT, 2016). In figure 11 the spatial distribution of the different natural areas in the Tempisque-Bebedero catchment system can be observed.

The national system of conservation areas SINAC was created under law N° 7788 by the Ministry of Environment and energy as a legal authority to manage and protect forestry, wildlife and use of river basins. To achieve the objectives of conservation and protection of natural areas the SINAC, 11 Conservation Areas were created in the whole country, one of them is the Tempisque conservation area (ACT) set up in the article 21 of the law mentioned before (Reglamento a la ley de Biodiversidad, 1998).

The protected areas have been classified by the government considering social, economic, cultural geographic and biotic elements with management purposes by the competent authorities. The following table (table 6) gives the distribution of natural areas according to the existing categories.

Table 6. Distribution of Protected Areas by Category

Management category	Number of wild areas	Terrestrial extension in ha	Marine extension in ha	Name of the protected area
Biological reserve	5	3976,71	1528	Cabo Blanco, Nicolás Wesserberg, Islas Negritos, Lomas de Barbudal and Guayabo
National parks	5	35289,9	22612	Baulas; Barra Honda and Diná, Rincón de la Vieja, Volcan Tenorio
Refugees of wild life		2107	8000	Ostional, Mata Redonda, Camaronal, Iguanita, Cipanci, Isla Chora, Romelia, Curú, Conchal, Werner Sauter, Caletas-Arío, El Viejo, La Nicoyana, Costa Esmeralda, Bosque Escondido,
State	6			
Mixed	5			
Private	4			
Wetlands (with decree)	3	20069	0	Corral de Piedra, Río Cañas, Palo verde Zapandi
Protected Zone	3	22902	0	Península de Nicoya, Cerro de la Cruz and Monte Alto
Total	**31**	**84344,61**	**32140**	

Source: (ACT, 2016, ACT, 2016)

3.6.2. Primarily vegetated: Terrestrial- Cultivated and managed areas

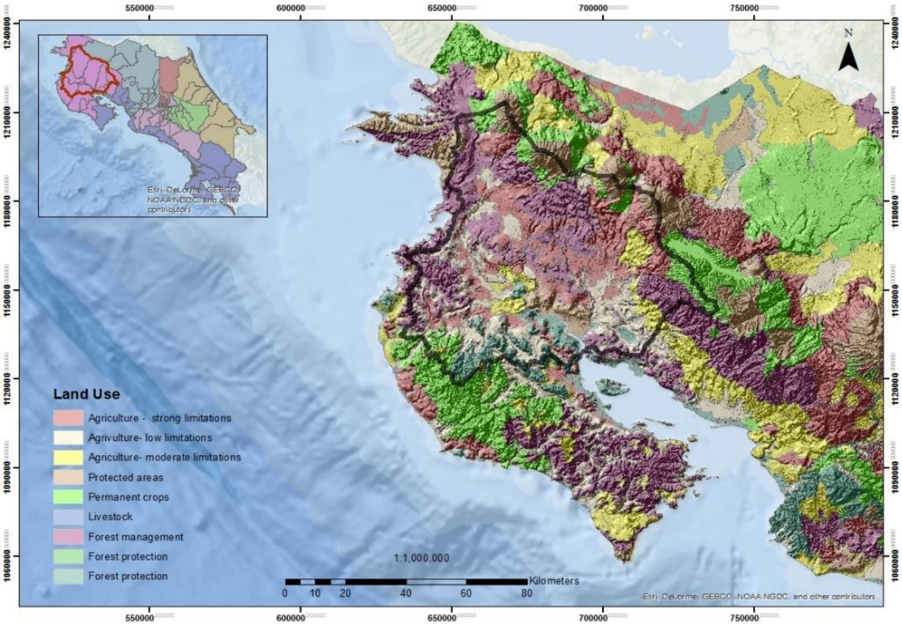

Figure 12 Land use in the Tempisque-Bebedero catchment system
Elaborated by the author based on: (Ortiz, 2014)

Guanacaste is one of the most important provinces in terms of agriculture, especially in the cultivation of basic grains such beans, maize and rice. The province is formed by 11 municipalities, all of them are dedicated to agricultural activities as a main economic activity for their population. According to Jiménez-Romȧn et al (2001) at least 29 different types of potential land uses have been identified inside of the Tempisque among wetlands, protected areas and cultivated zones (Figure 12).

3.7. Agricultural aspects of the basin

3.7.1. Main activities

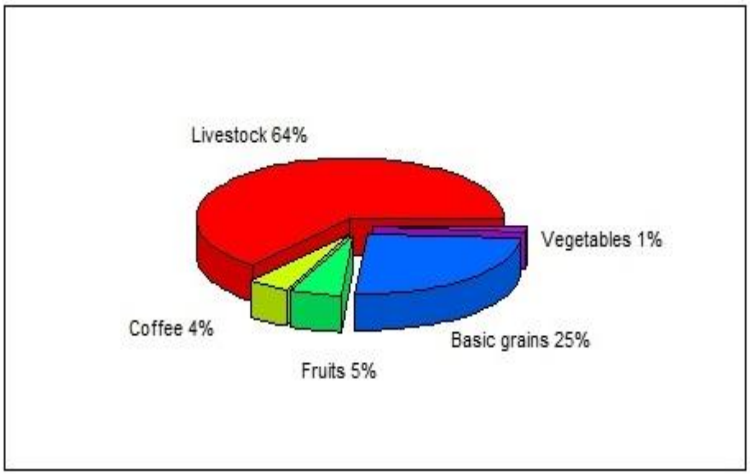

Figure 13 Types of economic activities in Guanacaste Elaborated by the author based on: (INEC, 2014a)

Among the main activities develop inside of the study area (Figure 13), are Livestock and cultivation of basic grains (rice, beans, maize etc.) as the most relevant for farmers according the National agricultural census elaborated by the National Institute of Statistics (INEC, 2014a) in which is described on detail the main products cultivated in Guanacaste based on the total number of existing farms.

Guanacaste occupies the fourth place in the country with the largest number of farms (table 7), and the first place with the largest area used for agricultural activities (Soto & Murillo, 2015), it means, although the number of farms is low in comparison with Alajuela which has 25176 (INEC, 2014a), its land use for agricultural purposes is bigger becoming one of the most important areas in crop production.

Table 7 Number of farms in Costa Rica

Province	**Total number of farms**	**Extension (ha)**
San José	18873	228247,30
Alajuela	25176	581968,60
Cartago	9558	92799,20
Heredia	5080	136884,80
Guancaste	***10885***	***592642,80***
Puntarenas	14467	514541,10
Limón	9008	259336,60
Costa Rica	**93017**	**2406420,40**

Source: (Soto & Murillo, 2015)

3.7.2. Rice crop

Rice is one of the most important grains in the basic diet of Costa Rican population and its production is in big part developed by small farmers in the whole area, however among Bagaces, Liberia, and, Santa Cruz districts are the highest annual production rates (SEPSA, 1989-2015).

As a rainfed crop, rice depends directly on monthly rainfall rate, it means that during prolonged dry seasons the plant is not able to supply completely its water requirements to grow and this long-term effect can be calculated in terms of yield crop.

According to the last census elaborated by the National Institute of Statistics (INEC, 2014a), until 2016, there were 1250 farms dedicated to rice cultivation, the 66,76% of them used their production for consumption and 22% for agroindustry purposes.

3.7.3. Irrigation system

Due to changes on annual precipitation patterns, rice crops are affected especially during months of low rainfall rate, between November and April; period in which the second sowing is expected. During May to October (rainy season) exists a period know as Mid-summer drought (in Spanish "Veranillo") characterized by an abnormal decline of precipitation during July and August. According to a research developed by Alfaro (2014) referring to the Mid-Summer Drought in the Tempisque-Bebedero catchment system during 1937 to 2012, this period has a mean duration of 45 days with an intensity of 6,6 mm per day.

Conforming to this tendency, irrigation constitute an essential tool to mitigate the effects of below-average precipitation presented in dry extended seasons. In those terms and according to statistics presented by the INEC (2014b) only the 23% of the existing rice farms use irrigation system, some of them as part of the Arenal-Tempisque irrigation project.

3.7.4. Access to crop insurances

One of the most important issues in the agricultural sector is the access to crop insurances, especially because by acquiring them increase the opportunity to get easier a bank credit, and make possible a higher economic stability by increasing the investment. Moreover, the agricultural good practices are benefited by crop insurances, promoting not only proper land use, but also improving the competitiveness.

According to the Comprehensive Crop Insurance Act (1969) in the comprehensive crop insurance act N° 4461, insurances are administered by the National Insurance Institute (INS), who determines the areas and cover crops the conditions under which the indemnities apply and the amounts payable by both parties.

Based on reports published by Executive secretary of agricultural sectoral planning (SEPSA, 1989-2015), one of the main grain insured by the Ins is the Rice crop, since being a rainfed crop is more prone to losses by natural hazards such as droughts. However, during the last five years, the INS has decreased the number of beneficiaries because of the increasing intensity of ENSO phenomena, recording losses of at least 4141 million of colones (₡) - equivalent to US$7 million during 2012 and 2015 (Baquero, 2016b)Figure 14 shows the historical record of insured area, the amount in colones (₡) and the total cultivated area in each year.

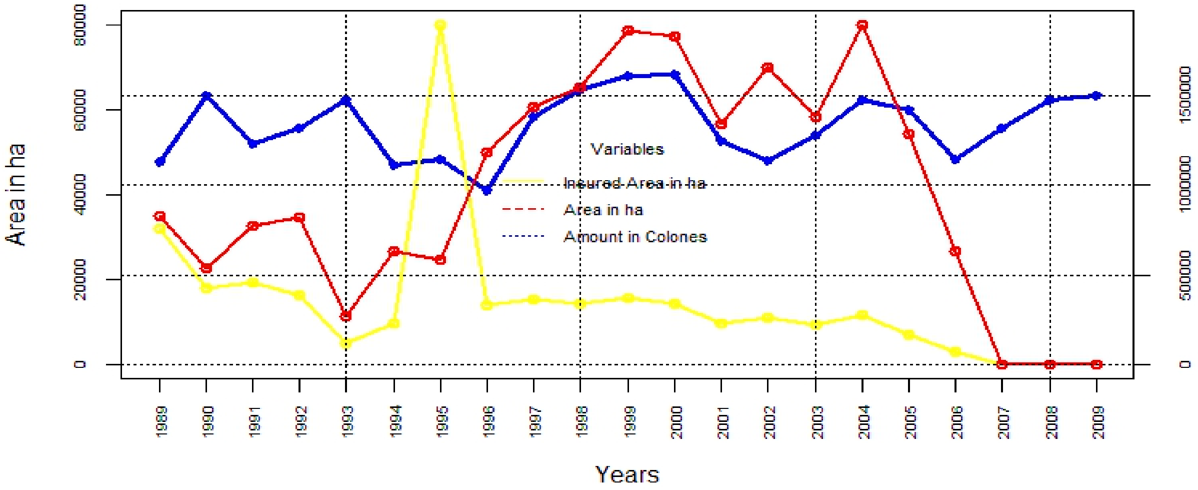

Figure 14 Historical insurances for rice crop
Elaborated by the author based on: (SEPSA, 1989-2015)

From 2007 to 2009, the agricultural sector did not acquire any insurance and since 2010 there are not official reports available about crop insurances. In January of 2016 the INS suspended the issuance of insurances owing to the economic losses produced between 2012 and 2015, the service was reactivated two months later (Baquero, 2016a).

According to the statistics presented above, only during 1995 the 90% of the total area was insured but in comparison with other years the average is around of 8,7 %, it means that great part of the zone has a high probability of low coping capacity and resilience in economic terms.

3.8. Data

As part of the methodological development of this research hydro-meteorological data were used to compute SPI and SDI indices. These data are a compilation of precipitation and streamflow time series from some gauging stations located in the study area. Each data set is explained in detail in the following sections.

3.8.1. Meteorological data

The meteorological data was provided by the National Meteorological Institute of Costa Rica (IMN), some of them with a monthly record of maximum and minimum precipitation values included in their reports. A set of 46 gauging stations for the whole catchment system and 15 for the 5 micro-watersheds in Tempisque and Bebedero. Some stations had a partial-full record length of 30 years and others had monthly gaps (Figure 15). Table 8 describes the available data of precipitation in the different gauging stations distributed in the Basin.

Table 8 Gaugin stations in Tempisque-Bebedero catchment system

TEMPISQUE

Watershed	Abbreviation	Stations	Longitude	Latitude	Elevation (m)	Period	
						From	To
Río tempisque- Río Tempisquito	SR	Santa Rosa	-85.6178	10.8364	299	1971	2015
	QG	Quebrada Grande	-85.5000	10.8500	326	1952	1986
	MG	Monte Galán	-85.5667	10.6333	46	1968	1985
	CD	Cañas dulces	-85.4833	10.7333	100	1968	1985
Río los ahogados	B	Borinquen	-85.4167	10.8167	577	1976	1985
	HA	Hacienda los Angeles	-85.4500	10.8667	572	1969	1974
Río Colorado	HG	Hacienda Guachilipin	-85.3833	10.7500	503	1968	1986
	CL	Colorado Liberia	-85.4833	10.6667	103	1971	1986
	HF	Hacienda la Flor	-85.5333	10.6500	62	1977	1986

BEBEDERO

Watersehd	Abbreviation	Stations	Longitude	Latitude	Elevation (m)	Period	
						From	To
Río Blanco	G	Guayabo	-85.2333	10.7000	556	1969	1979
	LF	La fortuna	-85.2000	10.6833	470	1976	1986
Río Tenorio	C	Cuipilapa	-85.1667	10.6667	475	1977	1986
	RN	Río Naranjo	-85.1000	10.6833	689	1981	1986
	RNB	Río Naranjo Bagaces	-85.0667	10.7000	543	1965	1969
	M	Montezuma	-85.0714	10.6817	501	1989	2016

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3.8.2. Hydrological data

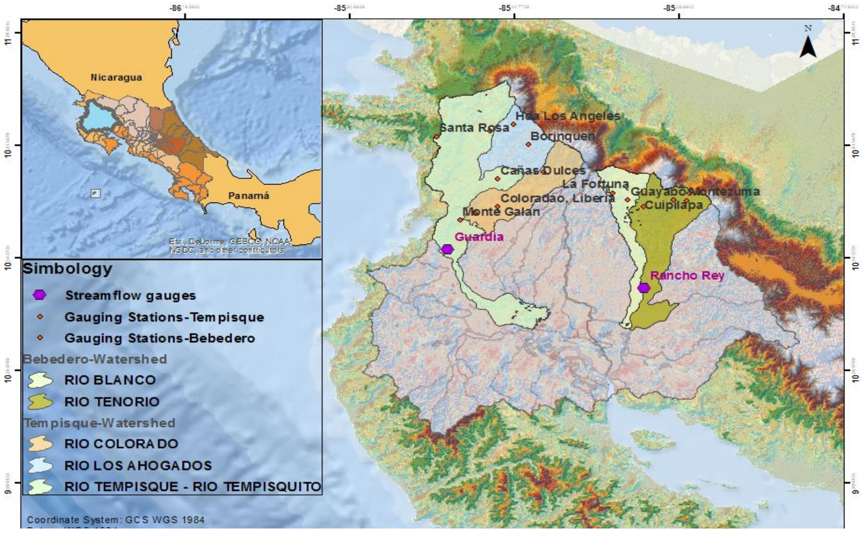


Figure 15 Hydrometric and meteorological stations in Tempisque-Bebedero catchment system
Elaborated by the author based on: (IMN, 1948-2016, Ortiz, 2014; UNESCO, 2007)

The streamflow data was provided by the ICE (Instituto Costarricense de Electricidad) with a common period from 1980 to 2003.

The zones in which the streamflow stations are located provide data with a low influence of pumping water for hydroelectric power generation, however, information regarding water extraction for irrigation was excluded mainly by the lack of complete historical data.

On the other hand, the data from station Rancho Rey was corrected by interpolation due to the existence of gaps in their records, while the station located in Guardia was obtained with a full length data record (Birkel, July/2005, p. 31). The description of the gauging stations is summarized in table 9.

Table 9 Gauging stations with monthly streamflow records

					Period	
ID	**Station name**	**Latitude**	**Longitude**	**Elevation**	**From**	**To**
1902	Guardia	10°33’49”	85°16’30”	13	Jan-1980	Dec-2003
2003	Rancho Rey	10°28’05”	85°09’52”	20	Jan-1973	Dec-2003

3.8.3. Agricultural data

The agricultural data was provided by the Executive Secretary of Agricultural Sectoral Planning (SEPSA) and complemented using León, Arroyo Blanco, & Barboza V research about production, technology and rice trade during the period 1950-2005 (2011).

The historical reports were elaborated with the support of the department of Economic Studies and Information in which a certain number of detailed statistics are described by year (SEPSA, 1990-2016) regarding to extension of land use for crops and total production of each product cultivated in Costa Rica.

4. METHODS

4.1. Filling of Rainfall data gaps

To complete the missing precipitation data, a monthly global rainfall data set with high-resolution station with a temporal coverage from 1900 to 2014 and a spatial resolution of ~25km provided by the NOAA/OAR/ESRL PSD was implemented to correct gaps in each meteorological station.

The source is a compilation of different updates of monthly total raingage-measured precipitation (P, mm), each value at each time-series station was differenced from the climatologically averaged P for that month which was available at or was interpolated spatially to the time-series station location (Matsuura & Willmott, 2012).

4.2. Standardized precipitation index (SPI)

The SPI index was calculated using R, a free software for statistical computing. The SPEI-R package developed by Veves (2012) based on drought monitoring methods McKee et al. (1993), was applied for this purpose using a long-term precipitation database from 1973 to 2016 to define rainfall deficits at different time scales. For this research, the temporal and spatial distribution of meteorological drought was analyzed at, 3, 6 and 12 months respectively

As follows, the procedure used to calculate the SPI index based on Wanders et al. (2010) is described.

The long-term records (X) are converted into log-normal values after zero values have been removed, to calculate the statistic U with (eq-1):

$$U = In\bar{X} - \frac{\sum In\ (X)}{N} \qquad (1)$$

Where N is the number of observations. The statistic U is then used for the calculation of two shape parameters (α and β) of the gamma distribution with (eq-2):

$$\propto = \frac{\bar{X}}{\beta} \qquad \beta = \frac{1 + \sqrt{1 + \frac{4U}{3}}}{4U} \qquad (2)$$

These shape parameters are then implemented in the basic equation of the gamma distribution (eq-3):

$$G(x) = \frac{\int_0^x x^{a-1} e^{\frac{-x}{\beta}} dx}{\beta^{\propto} \tau\,(\propto)} \qquad (3)$$

To account for the zero-values of precipitation in the long-term records a new cumulative probability function is introduced (eq-4):

$$H(x) = q + (1 - q)G\,(x) \qquad (4)$$

Where q is the percentage of zero-values. This new probability function is transformed into a standard normal random variable with mean zero and variance of one. The created random variable is the value of the SPI (Wanders et al., 2010, p. 29).

Once the SPI-3, SPI-6 and SPI-12 matrix were obtained, the results for each station were represented in charts to visualize the periods in which rainfall was abnormal, standing on threshold values given by literature to classify drought severity (Table 10).

Table 10 Classification of Standardized Precipitation Index

SPI value	Drought condition
2.0+	extremely wet
1,5 to 1,99	very wet
1,0 to 1,49	moderately wet
-,99 to ,99	near normal
-1,0 to -1,49	moderately dry
-1,5 to -1,99	severely dry
-2 and less	extremely dry

Source: (McKee et al., 1993)

4.3. Streamflow drought index (SDI)

The SDI was calculated using the DrinC software developed by the Centre for the Assessment of Natural Hazards & Proactive Planning and the Laboratory of Reclamation Works & Water Resources Management of the National Technical University of Athens. The principle to calculate SDI index is the same used in SPI calculation deriving the gamma probability density function; the only difference is that a monthly streamflow database is required to run the software (Tigkas, Vangelis, & Tsakiris, 2015).

According to the following equation, the SDI index can be calculated using existing data in which i denotes the hydrological year and j the month within that hydrological year (j=1 for

October and j=12 for September), Vi, k can be obtained based on the equation (eq-5): (Tigkas et al., 2015, p. 699).

$$V_{i,k} = \sum_{j=1}^{3k} Q_{i,j} i = 1,2,\ldots j = 1,2,\ldots,12\ k = 1,2,3,4 \qquad (5)$$

in which V i,k is the cumulative streamflow volume for the i-th hydrological year and the k-th reference period, k=1 for October-December, k=2 for October-March, k=3 for October-June, and k=4 for October-September. Based on the cumulative streamflow volumes Vi,k, the Streamflow Drought Index (SDI) is defined for each reference period k of the i-th hydrological year as follows (eq-6):

$$SDI_{i,k} = \frac{V_{i,k} - \bar{V}_k}{S_k} i = 1,2,\ldots,k = 1,2,3,4 \qquad (6)$$

According to Nalbantis I (2009) different types of hydrological drought can be defined using the results obtained of SDI calculation in each period of time. The classification criteria are described in table 11:

Table 11 Definition of states of hydrological drought with the aid of SDI

State	Description	Criterion
0	Non-drought	SDI ≥ 0.0
1	Mild-drought	-1,0 ≤SDI ≤ 0,0
2	Moderate drought	-1,5 ≤SDI ≤ 1,0
3	Severe drought	-2,0 ≤SDI ≤ 1,5
4	Extreme drought	SDI < -2,0

4.4. Characterization of meteorological drought

The characterization of meteorological drought was divided into two parts. Firstly, 15 gauging stations (see table 12) were used based on their geographical distribution to be able to correlate with hydrological data for the period of 1973-2003 (see table 9), due to recorded hydrological data are available only for this period. In summary, 3 watersheds for Tempisque and 2 for Bebedero were selected (see table 8). Secondly, all rainfall gauges located in the whole catchment system (In total 46 stations; 23 for each sub-basin) were considered to analyze the temporal and spatial behaviors during the period of 2004-2016.

For the characterization of meteorological drought in the study area an approach based on area average precipitation was implemented to calculate a regional representative SPI for each sub-basin using weighting values for each station and by averaging the SPI for 3, 6 and 12 months respectively.

Table 12 Number of meteorological stations located in each sub-basin

Sub-basin	Number of meteorological stations in the area	Streamflow stations
Tempisque	9	Guardia
Bebedero	6	Rancho Rey

4.4.1. Calculation of weighting values using the Thiessen Polygon method

The calculation of weighting values was based on the assignment of an influence area to each station with the annual mean precipitation of i-th times series using Arcmap 10.2.2 with the thiessen polygon tool.

The general formula used for each sub-basin is described as follows:

$$\boldsymbol{w_{i(Tempisque)}} = \frac{A_i}{T.area}; \qquad A_i = Thiesen\ polygon\ area\ of\ i - th\ stations \qquad (7)$$

$$\boldsymbol{T.area} = Total\ area\ of\ the\ sub - basin \rightarrow\ km^2$$

$$\sum_{i=1}^{n=9\ or\ 23} w1 + w2 + w3 \ldots wn = 1 \qquad \boldsymbol{n} = Number\ of\ stations$$

$$\boldsymbol{w_{i(Bebedero)}} = \frac{A_i}{Tarea}; \qquad A_i = Thiesen\ polygon\ area\ of\ i - th\ stations \qquad (8)$$

$$\boldsymbol{T.area} = Total\ area\ of\ the\ sub - basin\ \rightarrow\ km^2$$

$$\sum_{i=1}^{n=6\ or\ 23} w1 + w2 + w3 \ldots wn = 1 \qquad \boldsymbol{n} = Number\ of\ stations$$

4.4.2. Calculation of regional SPI

To calculate the regional SPI for each area Tempisque SPI_{RT} and Bebedero SPI_{RB}, the mean value of SPI from the time series selected on the time scale of 3, 6 and 12 months was computed for each station using the following expression:

$$SPI_{RT} = \sum_{i=1}^{n=23\ or\ 9} (\overline{SPI_{i-th}} * w_{i-th}) \qquad (9)$$

$$SPI_{RB} = \sum_{i=1}^{n=23\ or\ 6} (\overline{SPI_{i-th}} * w_{i-th}) \qquad (10)$$

$$\boldsymbol{n} = Number\ of\ stations\ ; \quad \overline{SPI} = mean\ of\ i - th\ stations\ at\ 3, 6\ months\ and\ 12\ months$$

4.4.3. Temporal drought characteristics using SDI and SPI indices

The characterization of meteorological and hydrological drought based on SPI and SDI analysis was considered to study temporal distribution of water deficit in terms of magnitude, frequency, intensity and duration.

Magnitude can be considered as the cumulative water deficit over a drought period (Thompson, 1999):

$$Drought\ Severity = \left\| -\sum_{i=1}^{n} SPIij \right\|$$

Where n is the number of months in which a drought event was present at j timescale.

The frequency was calculated using return period values; the interval between drought events at different magnitudes are expressed in months (Dalezios et al., 2000, 2000).On the other hand, drought intensity (LM) was defined as the ratio of drought magnitude over drought duration as (Suryabhagavan, 2017):

$$L_M = \frac{DM}{Dd}$$

4.5. Discharge deficits: Flow-duration curve and Threshold selection

The FDC (flow duration curve) was constructed based on Weibull plotting position by ranking values from monthly discharges, using number 1 for the highest value and n-th for the lowest. The plotted curve between monthly time-series of streamflow data and percent of time flow equally or exceeded represents the relationship in terms of magnitude and frequency of streamflow of the catchment system (Fennessey & Vogel, 1994).

The formula is described as follows:

$$p = \frac{100m}{n+1} \qquad (11)$$

Where, p is the exceedance probability, m is the raking number in descending order and n is the number of monthly flows (AgyeiAgyare, Atta-Darkwa, Kotei, Kyei-Baffour, & TakyiAtakora).

According to Sung & Chung (2014), the use of percentiles Q_{70}-Q_{90} derived from the FDC curve can be used as thresholds using long term data; this selection of threshold levels depends mainly on the objectives of the study area, the climate variability, physiographical catchment's characteristics and available data.

In the selection of threshold values for streamflow drought assessment, the low and high flow seasonality were considered to analyze flow anomalies during dry and rainy season. The values obtained for both seasons can be used as parameters of non-exceedance flow for granted volume for irrigation purposes or hydropower production etc.

4.6. Pearson correlation analysis among SPI, SDI, STI and rice yield.

For the analysis of the values obtained from SDI, SPI and yield anomalies in rice crop, the use of the Pearson correlation moment, well known as correlation coefficient (r) is required to measure the strength of the linear relationship among them, computed using the following formula:

$$r = \frac{1}{n}\sum_{i=1}^{n}\left(\frac{x-x}{S_x}\right)\left(\frac{y-y}{S_y}\right)(12)$$

where, xi and yi represent the values of arrays with 'n' number of elements being compared and x and y are the mean values of two arrays and Sx and Sy are the standard deviation of xi and yi respectively. The r measures the degree of similarity in variation about the means of two values (Jain, Pandey, Jain, & Byun, 2015, p. 4).

4.6.1. Drought and ENSO correlation

El Niño Southern Oscillation (ENSO) is a phenomenon produced by changes in the sea surface temperature in the tropical Pacific and in the ICZ (Intertropical convergence zone), these changes can be monitoring by different indicators such as SOI (The Southern Oscillation Index) and Sea Surface Temperature (SST) (Vu & Mishra, 2016). The Niño 3.4 Index is calculated from SST averaged anomalies over the Niño 3.4 region 5°North-5°South;170-120°West. This information was taken from (NOAA/NCEP CPC, 1950-present) website The correlation was computed and plotted using SPI values and SST El Niño 3.4, 3 and 1+2 anomaly values to interpret a drought relationship with ENSO events.

5. RESULTS

5.1. Correlation in the filling of Rainfall data gaps using Satellite imagery

To validate the use of this data sets a correlation test between observed data and satellite data was used for all gauging stations located in the study area. The results are shown in table 13.

Table 13 Correlation coefficients between in situ and satellite data

TEMPISQUE	**NOAA/OAR/ESRL PSD** r coefficient	**BEBEDERO**	**NOAA/OAR/ESRL PSD** r coefficient
Borinquen	0,87	Cuipilapa	0,84
Cañas Dulces	0,85		
Coloradao, Liberia	0,84	Fortuna	0,87
Hda Guachipilin	0,85	Guayabo	0,77
Hda La flor	0,73	Montezuma	0,77
Hda Los Angeles	0,86		
Monte Galan	0,78	Río Naranjo	0,90
Quebrada grande	0,89	Río Naranjo Bagaces	0,52
Santa Rosa	0,77		

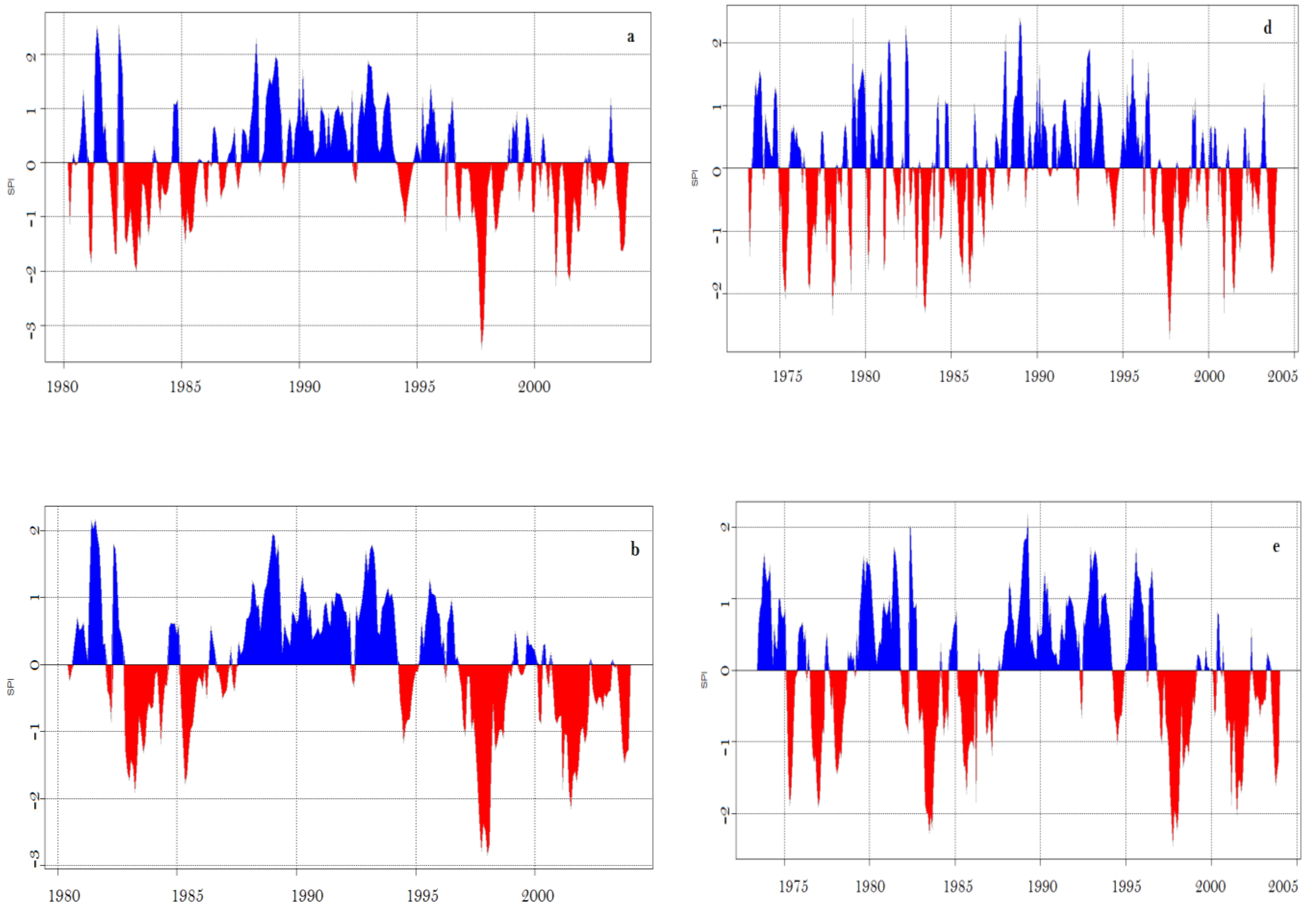
The correlation coefficients between satellite measurements and land observed data for precipitation, were above 0.8 in most cases, indicating that this product is suitable to complete gaps in rainfall data sets since it is a spatial-interpolated and cross validated product and moreover, has a good spatial-temporal resolution with a complete coverage in the study area.

5.2. Characterization of meteorological drought

As follows, are plotted the Regional SPI (3-6-12) for Tempisque and Bebedero for the period of 1973-2003 (Bebedero) and 1980-2003 (Tempisque) in which the anomalies in wetness (blue area) and dryness (red area) can be observed. Thus, a drought event starts when -1.0 value is reached and ends when SPI becomes positive again (Suryabhagavan, 2017).

5.2.1. Regional Standardized Precipitation Index in Tempisque (1980-2003) and Bebedero (1973-2003) catchment system

The SPI for Tempisque and Bebedero catchment system was calculated for the periods (1980-2003 SPI_{RT} and SPI_{RB} 1973-2003) at 3, 6 and 12 months respectively to analyze the seasonal estimation of precipitation and the overall crop yield and possible. From the calculation of these values, severity, duration and frequency statistics were computed. The temporal behavior of SPI is presented on Figures 16 (a, b, c d, e, and f).



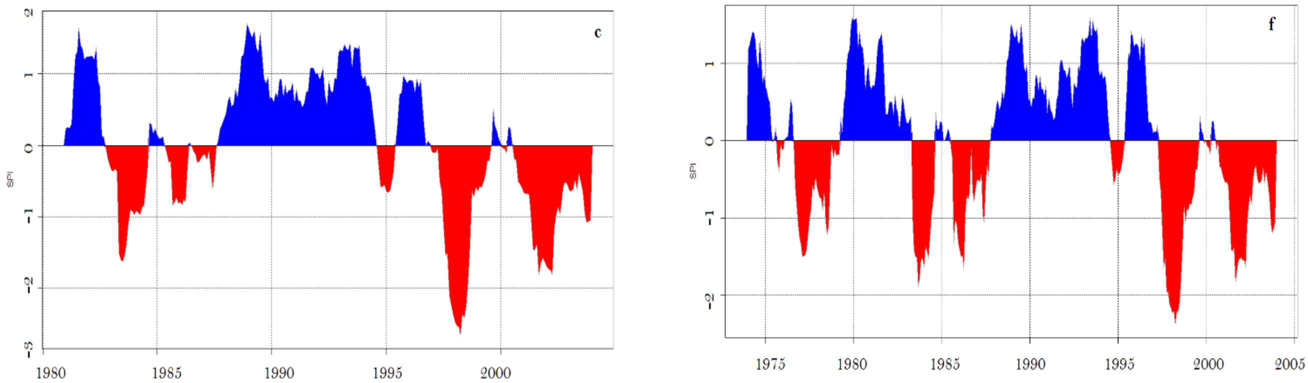


Figure 16 Standardized precipitation index: a) SPI-3, b) SPI-6, c) SPI-12 for Tempisque; d) SPI-3, e) SPI-6, f) SPI-12 Bebedero.

The SPI for both sub-basins at different time scales shows a remarkable difference in terms of frequency and duration of drought periods as long the time scale is increasing; a 3-month SPI shows more frequent drought events with a shorter duration compared with a 12-month SPI in which can be noticed persistent and longer shortfall rainfall periods. The intensities in both sub-basins at lower time scale are more variable, especially at 3-lagged month in which can be observed a higher fluctuation on events below -1.0 and above 1.0 probably as a response to climate, marked by strong seasonality during rainy and dry seasons. This behavior is also represented in figures 17 and 18 in which were split by watersheds and drought categories (*Mild-drought; moderate; severe and extreme*). As described in bar charts during the period 1973-2003 in Bebedero mild-drought events were more frequent in comparison with extreme events which were less frequent but with a longer duration at higher time scales, the same tendency can be observed for Tempisque during the period 1980-2003.

5.2.2. Drought frequency and severity

Based on the SPI_{RT} and SPI_{RB} at different time scales, the main characteristics for the catchment system in terms of duration, severity and intensity were derived, especially for common extreme periods presented in both areas. As a result, figures 17 and 18 describe the total of number of drought periods based on McKee et al., (1993) classification (Table 8) and mean duration per category for each watershed. However, is important to highlight that this information was obtained from a previous analysis from the total of gauging stations located in each region (Appendix C and D).

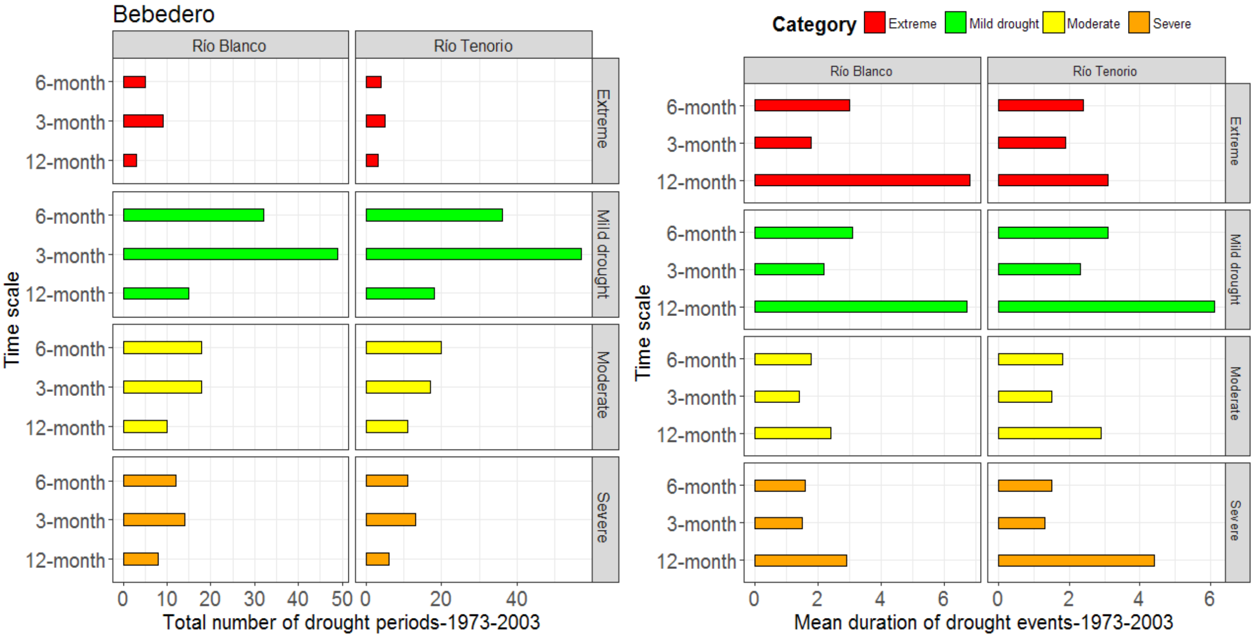


Figure 17 Total number of drought periods per category and mean duration in Bebedero watershed

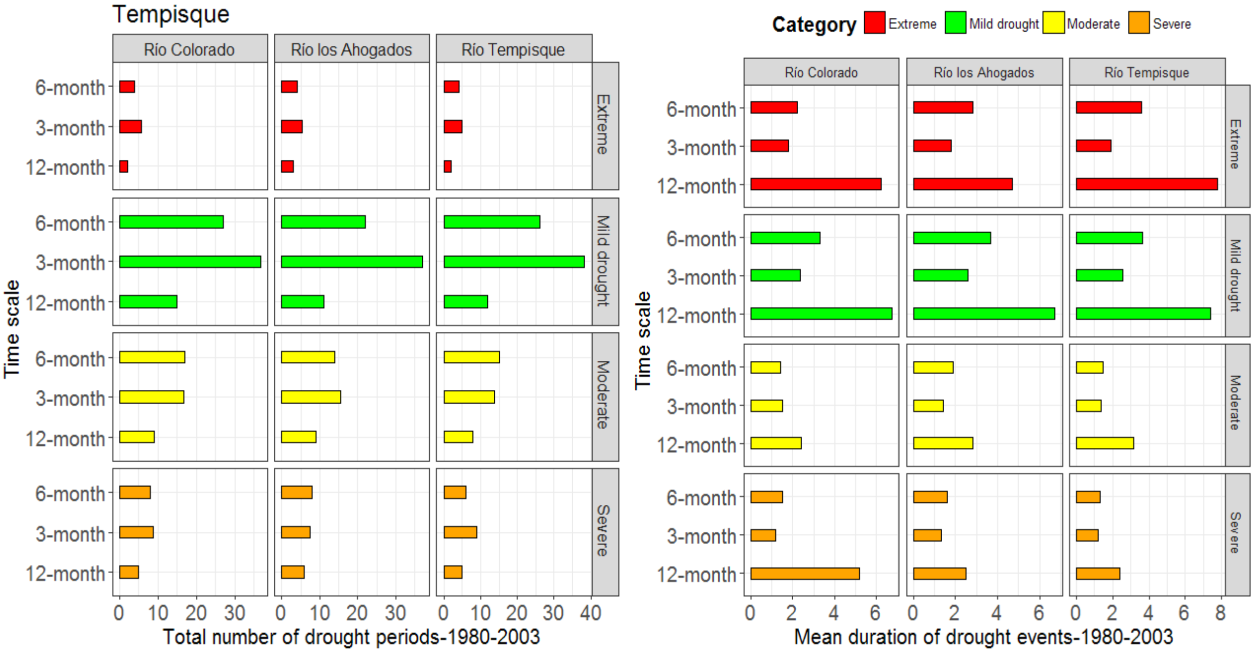


Figure 18 Total number of drought periods per category and mean duration in Tempisque watershed

In terms of mean duration of drought events per category, Tempisque presents notably greater mean durations in extreme periods in contrast with Bebedero whose mean duration do not exceed 4 months at 12-month SPI; time scale in which durations averages are usually more persistent.

In summarize, Tempisque experienced less number of drought events in all its categories but with a higher duration while in Bebedero occurred the opposite, the frequency of droughts was higher but its duration was lower, this can be explained by different circumstances, mainly because in Bebedero was analyzed a longer record period starting in 1973 to drive an analysis with correlation purposes based on existing hydrological data; however, even when if they had had common time series, starting in 1980 (Figure 16), the same conclusion is achieved.

Tables 14 and 15 summarize the most extreme events per category grouped by micro-watershed. Particularly for this research in Tempisque: Rio Tempisque-Tempisquito, Río Colorado Liberia and Rio Los Ahogados and for Bebedero: Rio Blanco and Rio Tenorio (see table 8) were selected in function of their relationship level with stream flow gauges for analytical purposes between SPI and SDI indices.

Table 14 Extreme drought values in Bebedero

Watersehd		**Río Blanco**						**Río Tenorio**					
Time scale		3		6		12		3		6		12	
		*E****	*D*****	*E*	*D*	*E*	*D*	*E*	*D*	*E*	*D*	*E*	*D*
Threshold	0 to -0.99	107	2,2	96,5	3,1	99,0	6,7	127,8	2,3	110,0	3,1	110,3	6,1
	-1.0 to -1.49	25,5	1,4	31,0	1,8	24,5	2,4	25,5	1,5	36,0	1,8	33,0	2,9
	-1.5 to -1.99	20,5	1,5	17,5	1,6	21,0	2,9	17,0	1,3	16,5	1,5	17,5	4,4
	-2.0 to less	15,5	1,8	15,0	3,0	17,5	6,8	10,0	1,9	9,3	2,4	10,0	3,1
Max. Duration	months	22,0		29,5		59,5		20,3		33,0		67,8	
Min. SPI	Year	***1975***	***1986***	***1975***	***1983***	***1975***	***1983***	***76,86,97***		***77,83,97***		***77,83,98***	
	Value (-)	4,5		5,3		2,7		2,8		2,7		2,4	
Min. Severity	Year	***1977-1979***	***1982-1984***	***1977-1979***	***1982-1984***	***1974-1979***	***1982-1987***	***77-78,84-85,96-99***		***76-77,85-87,96-00,00-03***		***75-79,96-03,97-99***	
	Value (-)	36,1		40,0		70,3		22,6		35,0		77,0	
	Intensity	1,66		1,71		1,19		1,14		1,20		1,20	
Max. Intensity	Year	***1974-1975***	***2000***	***1974-1976***	***1982-1984***	***1974-1979***	***1976-1979***	***73,86***		***76-77,82-84,96-99,00-03***		***75-79,83-84,96-03***	
	Value	2,69		2,00		1,32		1,83		1,35		1,29	

*: Number of total events per category; **Mean duration per category based on drought period

As observed in these tables, for both watersheds maximum duration of a complete drought period regardless of drought category was experimented at 12-month SPI; however, this trend keep constant in all the categories being especially longer in Mild-drought and extreme periods.

Table 15 Extreme drought values in Tempisque

Watersehd		**Río Tempisque-Río Tempisquito**						**Rio los Ahogados**						**Rio Colorado**					
Time scale		3		6		12		3		6		12		3		6		12	
		*E**	*D***	*E*	*D*	*E*	*D*	*E*	*D*	*E*	*D*	*E*	*D*	*E*	*D*	*E*	*D*	*E*	*D*
Threshold	0 to -0.99	95	3	93	4	88	7	95	3	78	4	70	7	85	2	90	3	91	7
	-1.0 to -1.49	19	1	21	1	24	3	22	1	25	2	23	3	26	2	24	1	22	2
	-1.5 to -1.99	12	1	9	1	12	2	10	1	12	2	14	2	10	1	13	2	16	5
	-2.0 to less	8	2	12	4	11	8	10	2	11	3	12	5	10	2	9	2	8	6
Max. Duration	months	20,3		29,5		42,5		22,0		34,5		46,5		19,0		34,0		46,0	
Min. SPI	Year	***1986-1997***		***83-98***		***83.86,98***		***83-97***		***83,97***		***83,98***		***82,85***		***80,84***		***83-98***	
	Value (-)	3,64		3,51		2,78		3,40		3,21		2,66		3,75		3,50		2,40	
Min. Severity	Year	***82-83,85-87,97-98***		***82-84,85-87,97-98,96-99***		***82-84,85-87,97-98,96-99***		***82-83.96-99***		***96-99,2000-03***		***99-03, 2000-03***		***82-83,83-84***		***82-85,97-99***		***82-86,97-99***	
	Value (-)	28,28		36,25		39,47		31,64		38,17		45,67		23,90		36,67		43,45	
	Intensity	1,41		1,43		1,77		1,58		1,13		0,98		1,32		1,19		1,08	
Max. Intensity	Year	***82-83,85-87,2003***		***82-84,8587,97-98,96-99***		***82-84.85-87,97-98,96-99***		***80,82-83***		***82-84,96-99***		***82-84,96-99***		***82-83,81***		***82-85,83-85***		***82-86,84-85***	
	Value	1,53		1,50		1,65		1,84		1,55		1,33		1,60		1,32		1,27	

*: Number of total events per category; **Mean duration per category based on drought periods

5.2.3. Spatial distribution of meteorological drought

An Inverse Distance Weighting (IDW) method was used to generate drought maps and visualize the spatial distribution of extreme events presented in both watersheds. In figure 19 is represented one of the most extreme events during 1997 with the highest duration and severity peaks for 3, 6 and 12 months- SPI.

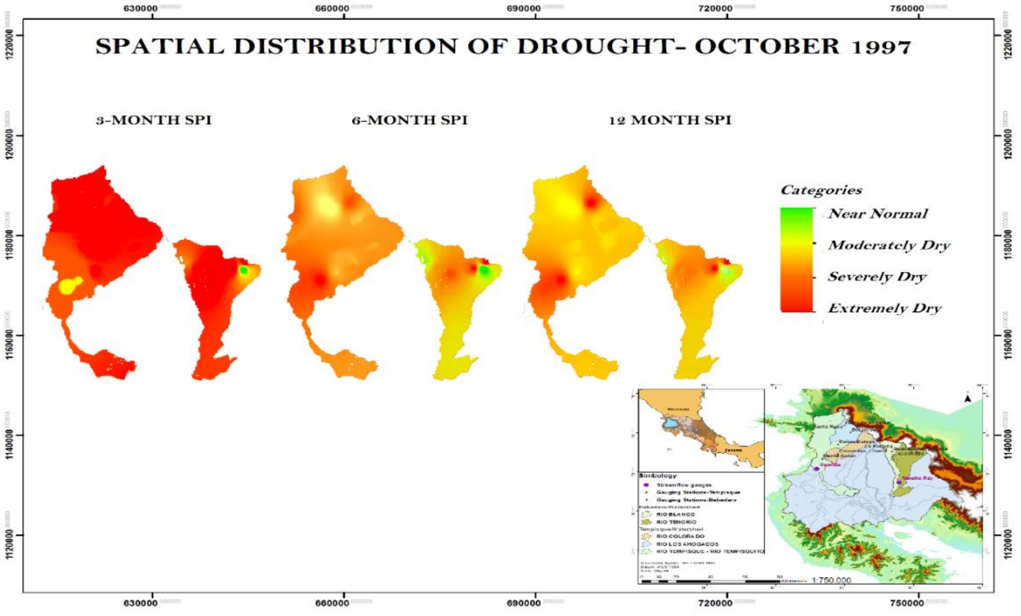


Figure 19 Spatial distribution of SPI in Tempisque and Bebedero

Figure 19 represents the spatial distribution of one of the strongest droughts presented in October of 1997 linked to El Niño phenomenon which started in April of 1997 reaching a temperature anomaly of -1.44 in July (NOAA, 2015) until develop its maximum intensity in October. Based on this, the map shows SPI values at different time scales where are clearly indicated the presence of an extreme drought across the watershed within Tempisque and Bebedero catchment system. In both watersheds can be appreciated how the area is changing its drought gradient to moderate dry as time- scale increases. At the northeast of Bebedero (*right image*), there was a persistent near normal drought at all time scales, while in Tempisque in the center of the map can notice how the moderate dry became an extreme drought at higher time scale.

5.3. Streamflow Drought Index (SDI)

5.3.1. Hydrological drought characterization

The hydrological drought characterization was based on SDI calculation using the negative values detected below the thresholds. The characteristics of each event can be determined by its duration, frequency, severity, and intensity as follows.

Figure 20 depicts the SDI index for each discharge station and shows the periods with a shortfall of streamflow during the period of 1980-2003 for Guardia and 1973-2003 for Rancho Rey station. Streamflow deficits are denoted by the red area composed by negative values which are classified by ranges (Figure 11) to describe each drought category

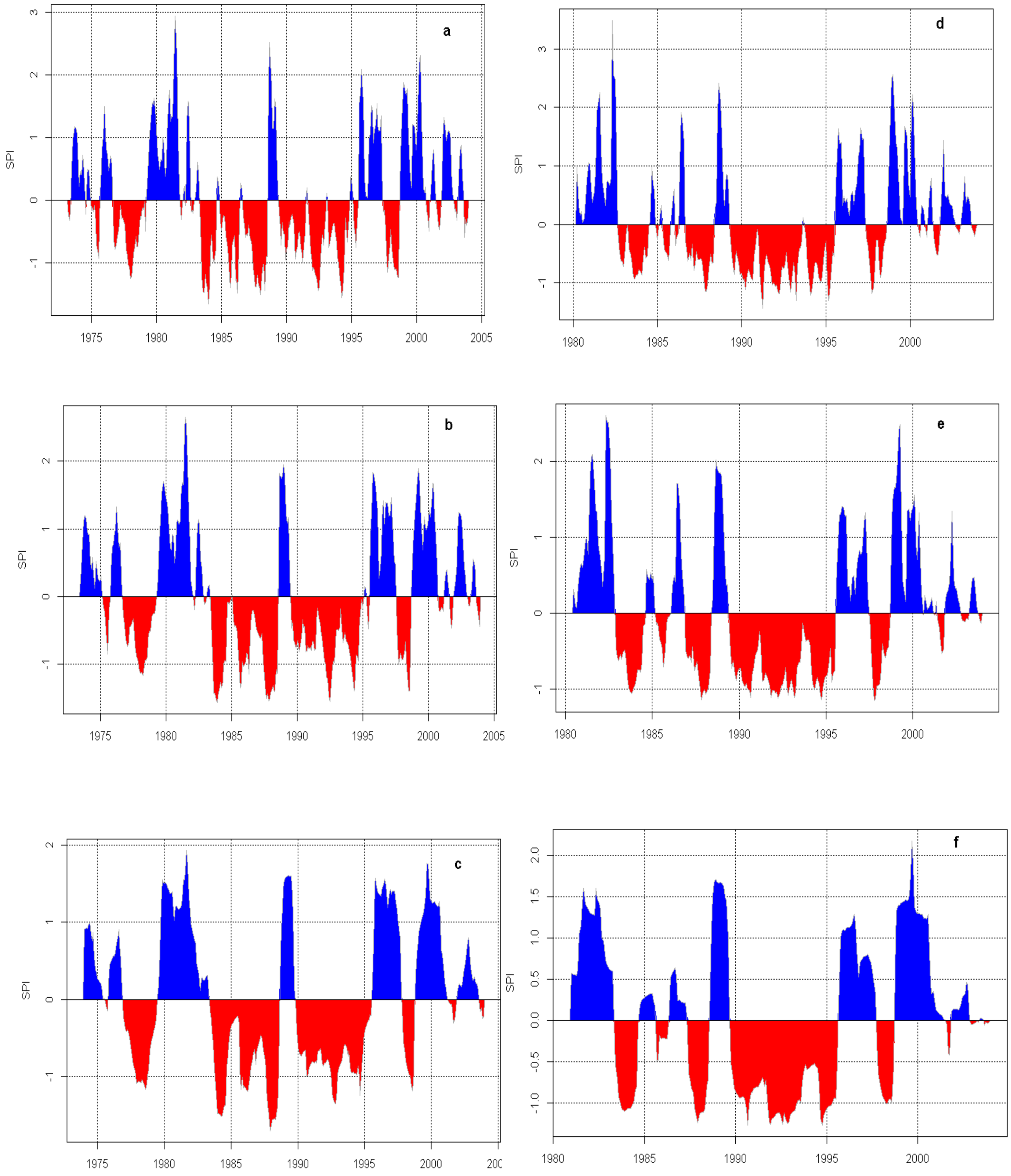


Figure 20 Streamflow drought index: a) SDI-3, b) SDI-6, c) SDI-12 Rancho Rey; d) SDI-3, e) SDI-6, f) SDI-12 Guardia.

As shown, in temporal distribution in the catchment system, drought events largely between 1982 and 1988, were more intense and longer but less frequent in Bebedero than in Tempisque; in this range of period at 3-month SDI Tempisque reflected a larger number of drought periods interrupted by relevant non-drought events with a short duration but with an intensity above +0.8, while in Bebedero, drought periods were characterized by their shorter frequency and larger duration accompanied by a less frequent number of non-drought periods. This tendency was constant during 6 and 12-month SDI, just with some variations on duration, being more longer as time-scale increases.

In contrast, it is important to highlight periods where both sub-basins had the same behavior; as an example, one of the largest hydrological droughts had its onset in 05.1989 until 07.1995 reaching its highest intensity at 12-month. As can notice the onset period was during the beginning of the rainy season (Appendix A and B), a period in which the beginning of high flow season is expected, nevertheless, the major recharge season is given among September, October and November, months in which the highest absolute values of intensity were experienced.

5.3.2. Calculation of discharge deficit using the threshold selection method

The flow duration curve is widely used to characterized hydrological drought periods by plotting the cumulative frequency of the streamflow as a function of the percentage of time that streamflow is equaled or exceeded (Bouvier et al., 2009). In the case of Tempisque (Guardia Station) and Bebedero (Rancho Rey station) catchment system, were used percentiles Q70 as thresholds for high flow and low flow, these results can be observed in table [16].

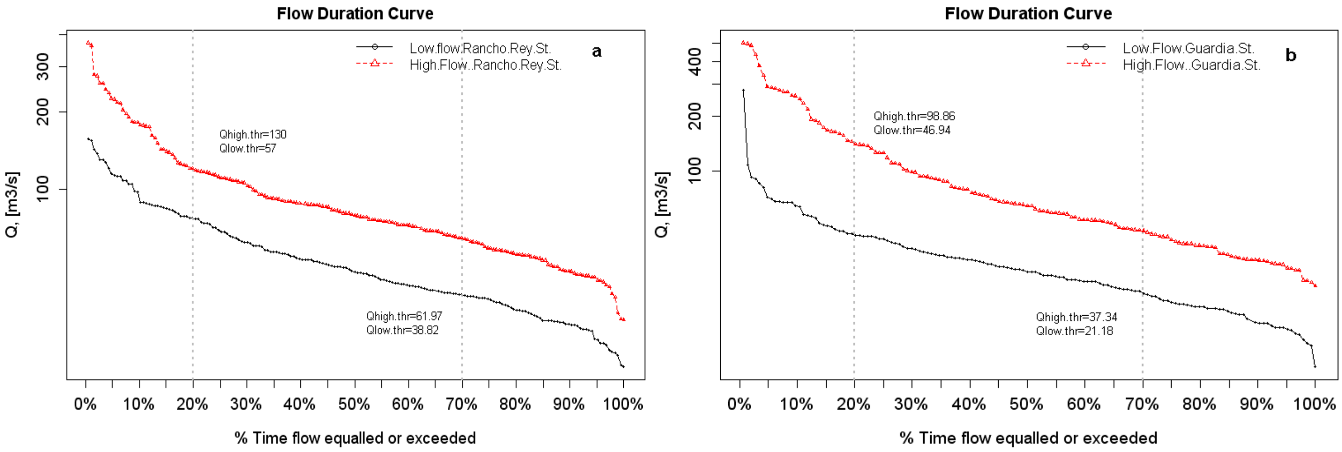


Figure 21 Flow duration curve: a) Rancho Rey station and b) Guardia station

Exist many factors which determine the shape of the curve, among them, the physiographic characteristics of the area that according to Monge-Nájera (2004) in Guanacaste can be described as a plateau. The little slope of the curves shows the behavior of flow regime and reflects the catchment's response to precipitation and the storage capacity. For this research, a seasonal constant threshold was calculated based on a clear high and low flow season.

Considering that do not exist wide climatic differences between both sub-basins, it is normal to expect quite similar shape of the two curves, however, it can be perceived a few little variations (Appendix G) during high-flows region as a result of higher precipitation rates in Tempisque and as well in the low-flow region probably justified by a higher monthly evapotranspiration rate and less runoff in the area in comparison with Bebedero (UNESCO, 2007). Furthermore, this could also be associated that in Tempisque hydrological drought periods were more frequent [See Section] than in Bebedero, and meteorological drought events had a longer duration mainly at the extreme category (See Section).

Table 16 Statistical data provided by FDC

Time series	Low Flow Rancho Rey St.	High Flow Rancho Rey St.
Min date: :1973-01	Min. : 20.31	Min. : 30.94
	LF-Q_{70}. : 38.82	**LF-Q_{70}.** : 57
	Median : 47.38	Median : 78.77
	Mean : 55.77	Mean : 96.50
	HF-Q_{70}. : 61.97	HF-Q_{70} : 130
Max. date :2003-12	Max. :157.50	Max. : 371.30
Time series	**Low Flow Guardia St.**	**High Flow Guardia St.**
Min date: :1980-01	Min. : 8.42	Min. : 23.43
	LF-Q_{70}. : 21.18	**LF-Q_{70}** : 46.94
	Median : 27.95	Median : 64.20
	Mean :34.44	Mean : 100.86
	HF-Q_{70}. : 37.34	HF-Q_{70} : 98.86
Max. date :2003-12	Max. : 275.67	Max. : 503.34

Table 16 shows the statistical values obtained from the FDC, among them the thresholds values for low flow season and high flow season.

5.3.2.1. Correlations between duration and severity values based on threshold level

The total number of months with discharge deficits were counted using different percentile values (Table 17) to compare sensitivity in detecting streamflow exceedance, especially during rainy season.

Table 17 discharge deficit events

Rancho Rey				
	Total number of months with discharge deficit			
Time scale	1-month	3-months	6-months	12-months
Seasonal threshold Q_{70}	97	91	81	48
Fixed threshold Q_{70}	112	98	69	17
Fixed threshold Q_{90}	37	26	4	0
Guardia				
Time scale	1-month	3-months	6-months	12-months
Seasonal threshold Q_{70}	86	79	82	53
Fixed threshold Q_{70}	87	78	49	0
Fixed threshold Q_{90}	29	19	0	0

To validate the implementation of a seasonal threshold, a correlation test was running to compare the differences among the three thresholds levels (Seasonal Q_{70}, fixed Q_{70}, and fixed Q_{90}) on water deficits and durations as shown in matrix 22 and 23.

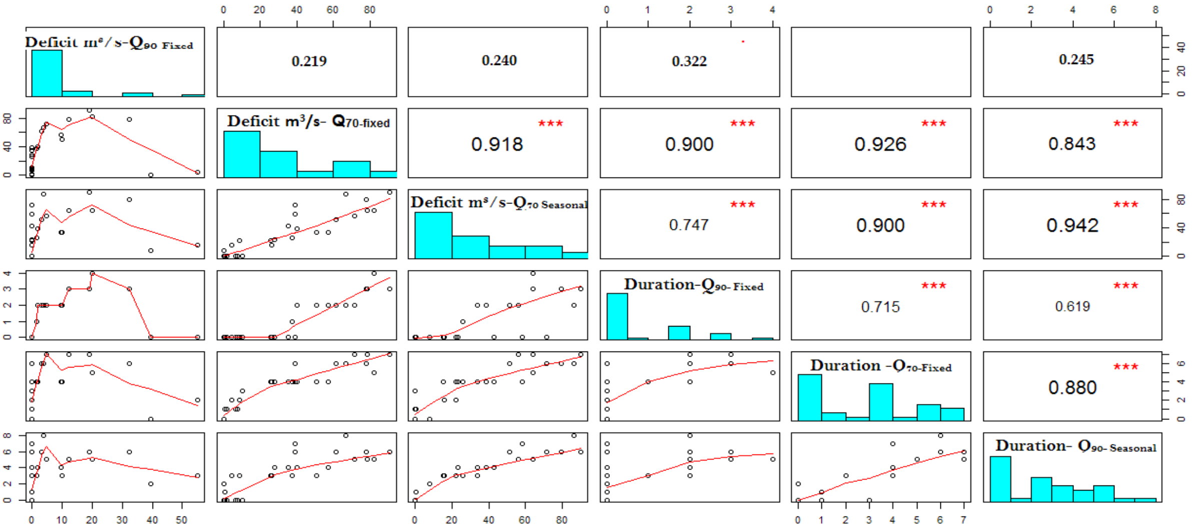


Figure 22 Correlations between durations and severities of the three threshold levels in Bebedero- (Rancho Rey station)

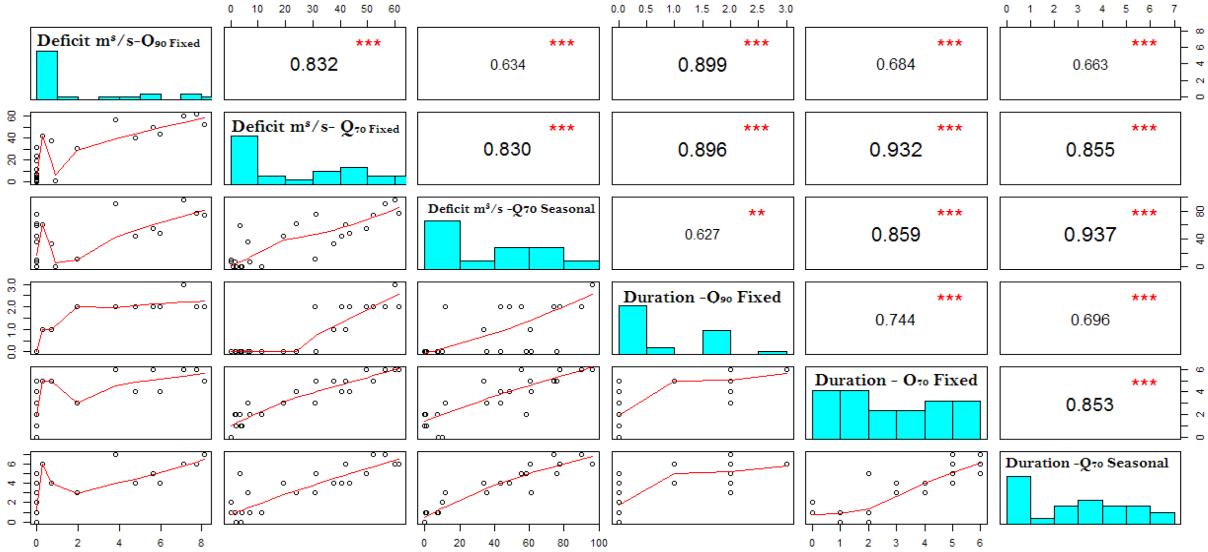


Figure 23 Correlations between the durations and the severities of the three threshold levels in Tempisque- (Guardia station)

The highest values were associated with a seasonal Q_{70} threshold followed by the fixed Q_{70} threshold with a small interval of difference, nevertheless, a fixed Q_{90} threshold exhibited a wider difference below 0.5. Likewise, in table 17 are outlined the total number of months with discharge deficit, in which is denoted the highly sensitivity of seasonal threshold level in detecting streamflow variations at higher time scales in comparison with fixed thresholds; this is mostly because at larger time scale the extreme values are smoothed by averaging and those values cannot be detected using a Q_{90} percentile.

The calculated values were summarized based on SDI and discharge deficits; in table 18 are described the major hydrological drought events characterized according to their duration, intensity and severity values. As result, mild drought events were more frequent and with a longer duration at all time scales, at least for Tempisque while in Bebedero (*Rancho Rey St*.) at 12-SDI, moderate droughts were longer but less frequent and with not any extreme and severe drought period registered. In terms of intensity, the most outstanding peaks were experimented in 1983,1984 and 1997 mainly during the month of August, September, October, and, November, and the lowest discharge deficit for both sub-basins was developed in June in most of the cases.

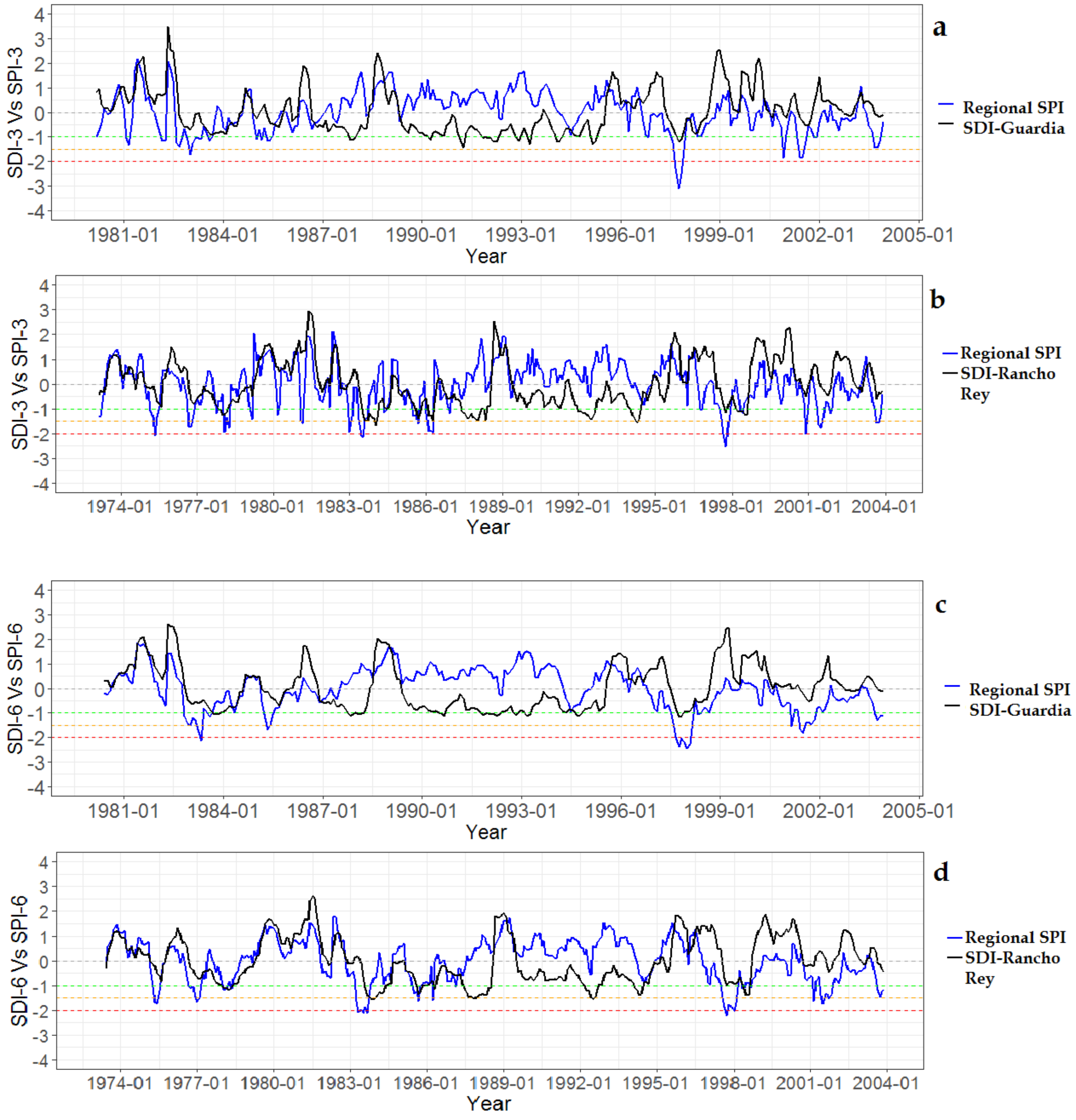
The onset month in which a hydrological drought was developed varies from September, October during the rainy season and from February and March during the dry season, the end was often presented at the beginning of the rainy season or during the high recharge season.

Table 18 Major hydrological drought events in Tempisque-Bebedero catchment

	Time scale	Threshold	Intensity	Mean duration of drought events per category	Number of events	Duration of total drought events (Months)		Year		Intensity(-)	Discharge deficit (Based on FDC -threshold values (Q70)		
Rancho Rey													
			Category	months		Mean	Max	Min. SPI value	Month	Min. Value	Year	Min. Value m^3/s	Month
SDI	3	0 to -0.99	*Mild drought*	5.45	158	11.05	31	1984	January	-1.66	1992	-30.46	June
		-1 to -1.49	*Moderate drought*	3.77	49								
		-1.5 to -1.99	*Severe drought*	1.00	3								
		-2.0 and less	*Extreme drought*	0	0								
	6	0 to -0.99	*Mild drought*	7.18	158	14.79	67	1983	December	-1.56	1992	-26.27	June
		-1 to -1.49	*Moderate drought*	3.31	43								
		-1.5 to -1.99	*Severe drought*	1.50	6								
		-2.0 and less	*Extreme drought*	0	0								
	12	0 to -0.99	*Mild drought*	10.21	143	27.29	69	1987	October	-1.70	1984	-14.36	June
		-1 to -1.49	*Moderate drought*	4.44	40								
		-1.5 to -1.99	*Severe drought*	4.00	8								
		-2.0 and less	*Extreme drought*	0	0								
Guardia													
			Category	months		Mean	Max	Min. SPI value	Month	Min. Value	Year	Min. Value m^3/s	Month
SDI	3	0 to -0.99	*Mild drought*	6.22	143	11.64	52	1991	April	-1.43	1990	-29.69	June
		-1 to -1.49	*Moderate drought*	2.00	20								
		-1.5 to -1.99	*Severe drought*	0	0								
		-2.0 and less	*Extreme drought*	0	0								
	6	0 to -0.99	*Mild drought*	6.89	131	15.60	74	1997	October	-1.15	1992	-28.03	June
		-1 to -1.49	*Moderate drought*	2.78	25								
		-1.5 to -1.99	*Severe drought*	0	0								
		-2.0 and less	*Extreme drought*	0	0								
	12	0 to -0.99	*Mild drought*	5.80	87	17.13	71	1990	September	-1.27	1992	-15.26	July
		-1 to -1.49	*Moderate drought*	7.14	50								
		-1.5 to -1.99	*Severe drought*	0	0								
		-2.0 and less	*Extreme drought*	0	0								

5.4. Drought propagation

Drought propagates throughout the hydrological cycle showing in some cases remarkable changes on streamflow regime. To observe those variations the SPI and SDI time series were plotted at different time scales to compare how rainfall could have had a direct effect on discharge deficit.



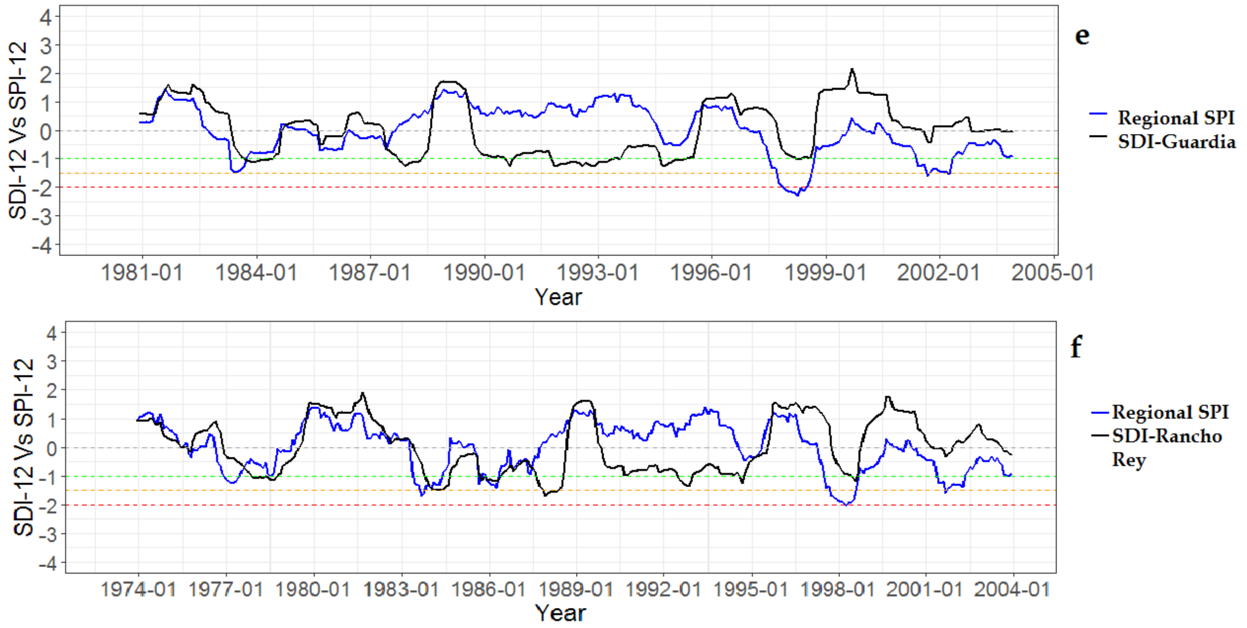


Figure 24 Temporal behavior between Regional SPI and SDI in Tempisque-Bebedero: SPI_{RT} (a, c, e) for 3, 6 and 12 - months and SPI_{RB} (b, d, e) for 3, 6 and 12 months

The SPI and SDI indices assessed for Tempisque and Bebedero catchment system are an important tool to understand how the hydrological cycle behaved and propagated throughout the time, especially during water scarcity periods. In the plotted time series are similar behaviors for both sub-basins, as example, during the period 05.1989 to 07.1995 there was a significant difference between rainfall anomalies and streamflow anomalies which decreased until developing a prolonged mild-drought period whereas precipitation had a positive behavior categorized as near-normal. To analyze the strength of the influence of precipitation on streamflow, correlation tests per station and by region were calculated as indicate figure 25 in where can be appreciated the Pearson coefficients distributed in a heat-map plot.

5.5. Correlation and trends

Correlation coefficients are based on Pearson concept which evaluates an existing relationship between two variables describing its direction and strength. From the SPI time series obtained per station and Regional SPI (SPI_{RT} and SPI_{RB}) and the SDI in each watershed were calculated the Pearson coefficients as represented in the heat-maps (Figure 25 [a and b])

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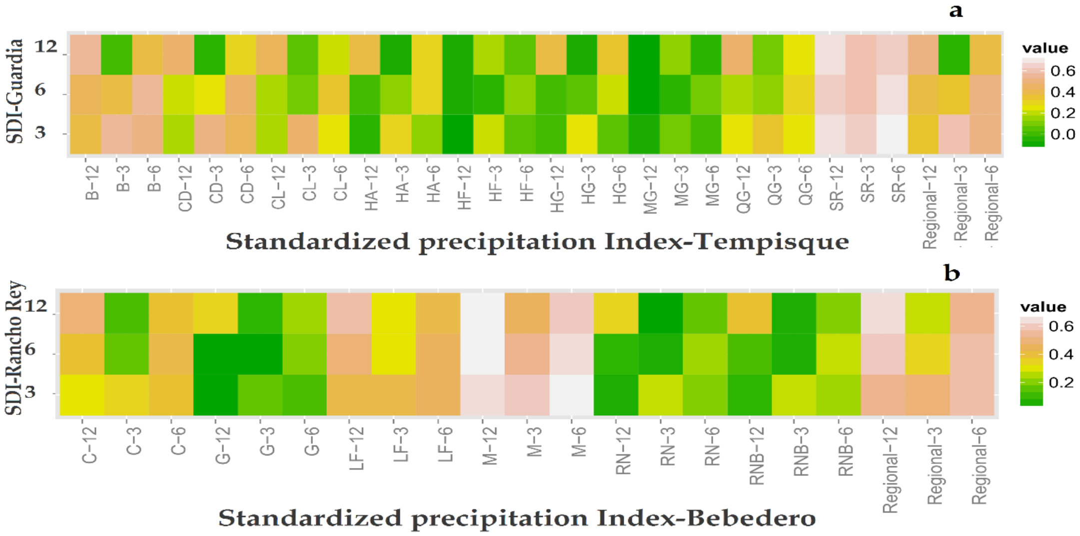

*For abbreviations see (Table 8)

Figure 25 Pearson coefficients between SPI and SDI indices

The highest values were obtained at 3-month lagged SDI and 6-month SPI, while at 12-month were registered the lowest values for both areas, this temporal behavior can be observed as well in figures 24.

5.5.1. Drought frequency and duration: Meteorological and Hydrological drought

Drought frequency and duration are represented in Figures 26 and 27 for the regional SPI in Tempisque and Bebedero, which were compared with the drought assessment analysis based on SDI data obtained from each streamflow gauge.

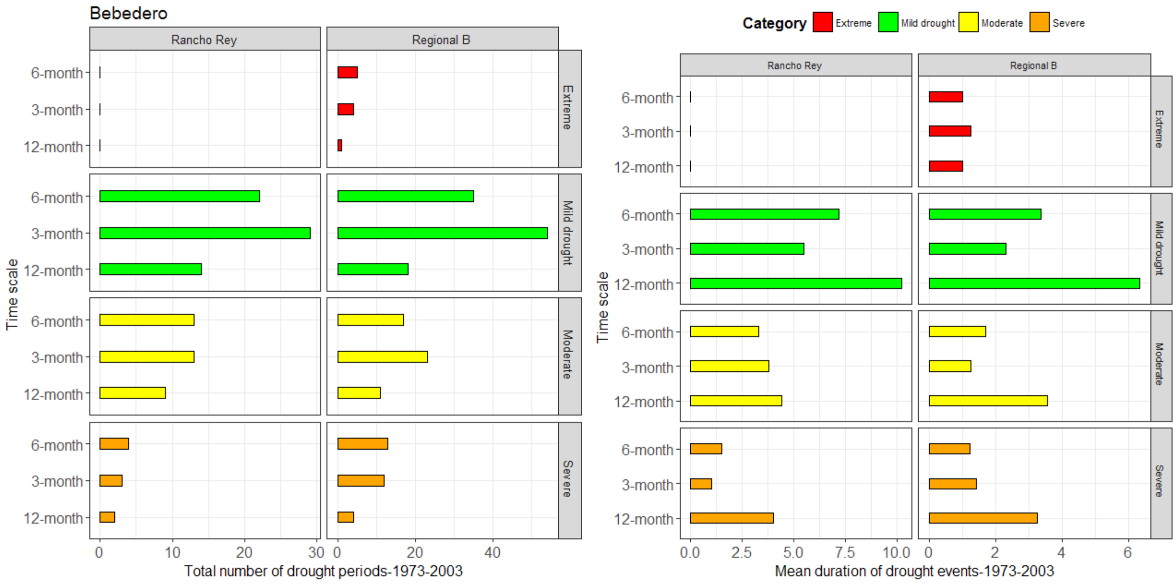

Figure 26 Comparison of the total number of drought periods per category and mean duration in Bebedero based on SPI and SDI indices

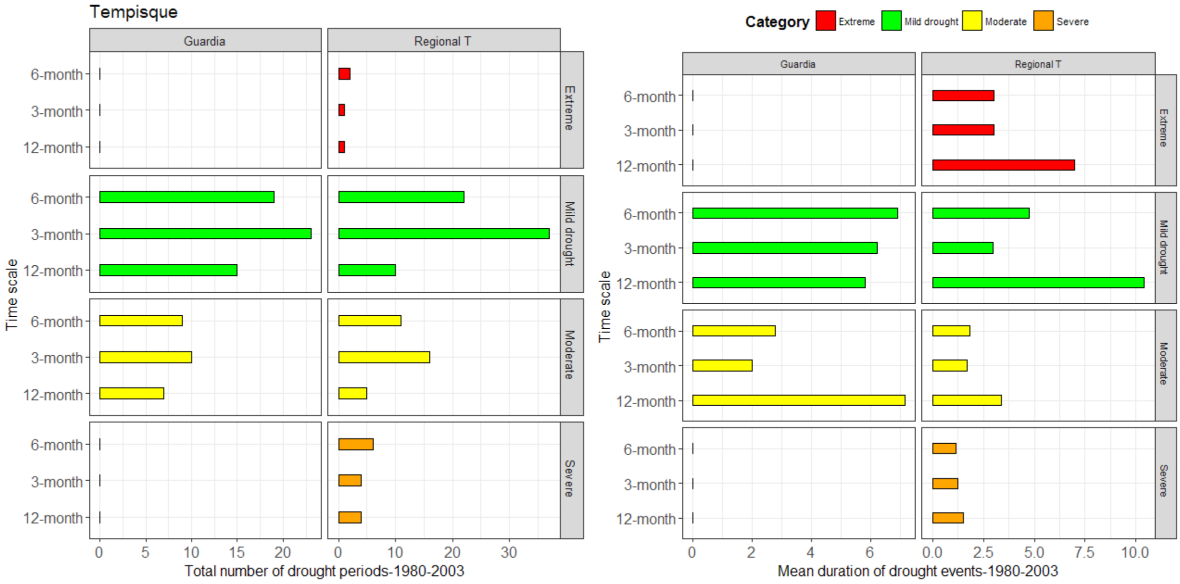

Figure 27 Comparison of the total number of drought periods per category and mean duration in Tempisque based on SPI and SDI indices

As described in figures 26 and 27 and explained previously, Bebedero presented more frequent meteorological drought periods from 1980 to 2003 but with a less longer duration in contrast with Tempisque, this tendency was permanent at all time scales and intensity categories; however, in spite, were more pronounced the amount of drought periods in Bebedero, the hydrological drought presented in the area had opposite behavior principally in the categories of mild-drought, moderate and severe drought; the frequency of events was lower nevertheless, their mean duration was longer in comparison with the results obtained in the SPI characterization.

Meteorological drought in Tempisque was more frequent compared to hydrological drought, especially in severe and extreme categories in which there were none hydrological drought episodes reported. The major trend is that as the time scale increases, the duration becomes longer, at least for meteorological events.

Additionally, note that in the meteorological severe category Bebedero and Tempisque had a similar behavior in terms of duration on a 12-month scale, both were around 4 months, however, the response of hydrological drought at the same category differs because in Bebedero while mean duration was almost equal to meteorological drought in Tempisque was presented the contrary situation, the hydrological drought lasted around 6 months.

5.6. Drought correlation on rice yield

Drought indices were used to run a correlation test with annual rice yield anomalies values as one of the most important and dominant crops in the study area. The grain is cultivated in most of the cantons of the province especially in Bagaces and Cañas in Bebedero and Liberia, Santa Cruz and Nicoya in Tempisque.

For the Pearson correlation test (Figure 29), was used the annual yield anomalies values with 12-months lagged SPI, SDI and STT El Niño 3.4,3 and 1+2; the time series were plotted (Figure 28 [a-b]) to observe temporal behaviors in both watersheds.

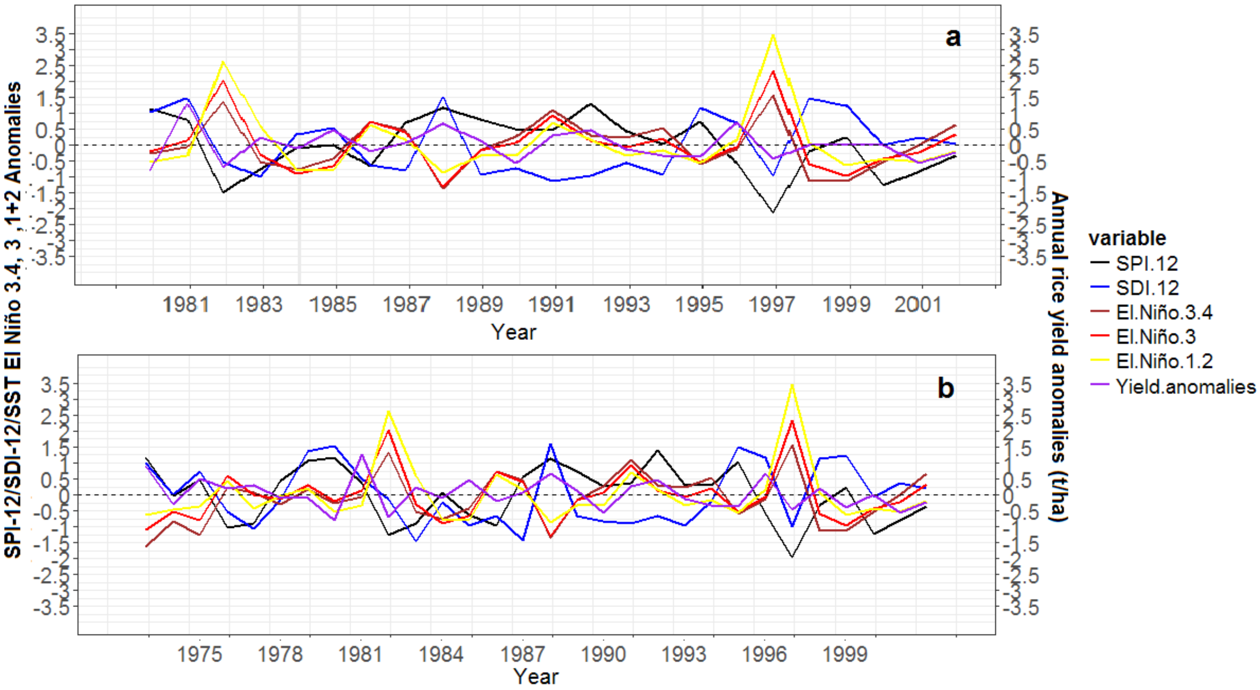

Figure 28 Time series SPI-12, SDI-12, SST El Niño 3.4, 3 and 1+2 and Rice yield anomalies in Tempisque (a) and Bebedero (b)

In figure 28 are plotted the time series for each index and the annual rice yield anomalies, as it may be observed rice crop presented four evident periods where yield dropped considerably in 1982-83, 1990-91, 1997-98 and 1998-99.

As an example, in 1982-1983 rice yield declined as well as precipitation. As it may be noticed SST index indicated the presence of ENSO phenomena; during this year, El Niño started in July and reached its highest point in December of 1984, this information is based on El Niño index in the region 3.4 (Figure 30); in the region 3, the phenomena began in 04/1982 with a high peak in 12/1982 until 06/1983, also in the region 1+2, El Niño developed its biggest intensity in 06/1983 (+4.56) until September. These trends indicate the influence of El Niño on rice yield behavior due to its strong severity and the periods in which it developed its highest intensity values; all of them had place during the rainy season, time of the year in which the first sown is usually performed.

To corroborate the dependence level of Sea surface temperature anomalies on meteorological and hydrological drought events as well on rice yield anomalies a correlation analysis was used as shown graphically in correlation matrices[1] (Figure 29). As observed, for Tempisque and Bebedero exist a significant influence of regional circulation (*El Niño 1+2*) on rainfall variability, however, in contrast, streamflow variation seems to be more correlated to global patterns (El Niño 3.4). Additionally, rice yield anomalies were more correlated with 12-lagged month SPI than SDI, especially in Bebedero in which is observed a non-significant dependence.

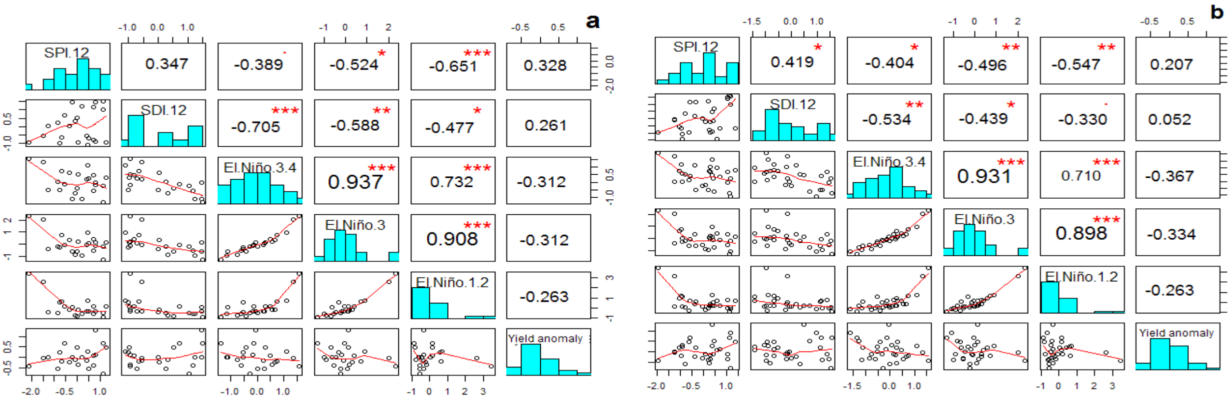

Figure 29 Pearson correlation values for SPI-12, SDI-12, SST-12 and Rice yield in Tempisque (a)-Bebedero (b) catchment system

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[1] Significance level: (α=0.001, 0.01, 0.05, 0.1, 1) <=> Symbols (“***”, “**”, “*”, “.”, “”)

5.7. ENSO correlation with rice yield-1973-2003

In Costa Rica most of the drought events have been directly related to ENSO phases during dry periods, for example in the North Pacific region (Chorotega[2]) more than 90% of drought events in the last 40 years were associated with ENSO dry seasons and many of these cases have brought agricultural losses and critical socioeconomic impacts especially in the rice sector (Villalobos, Retana, Zúñiga, & Ríos, 1997).

The main impacts on Rice yield associated to ENSO phenomena are summarized in table 19, this is a composite of different sources of information such as newspapers, reports, official documents etc., that describes the effects in economic terms and percentage of the damages in planted area. Moreover, it may be appreciated that all the years reported corresponding to El Niño event (Appendix F). Additionally, in figure 31 is plotted in a bar chart the rice yield in terms of anomalies and percentage of variation and the categories based on intensity values of the ENSO phenomena.

Table 19 Drought impacts in Guanacaste

ENSO	Type of crop	Impact	Data source
1973	*Rice*	36800 tons lost	La Nación 1973
1976		75% lost of the planted area	Arroyo and Paterson 1988
1977		7000 ha lost Losses in Carillo and Santa Cruz	Arroyo and Paterson 1989
1982		₡500 million lost	La Nación 1982
1983		10,000 Ha of planted area suspended	Vega 1983
1986		₡6 million lost	OMM 1987
1991		2000 Ha lost of the planted area	Leitón 1991
1994		₡160 million lost	Fuentes 1994
1997		80% of the production affected	Agüero 1998

(Villalobos & Retana, 2000)

In figure 36 can be observed the correlation coefficients between SPI, ENSO indices and temperature for the period 1980-2016. The result of the complete time series showed a high correlation between SPI at 12-month time scale and ENSO indices for both watersheds; all the coefficients were above -0.7 ($\alpha=0.001$), however the dependence of temperature and SPI-12 was higher in Tempisque than in Bebedero.

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[2] Costa rica is divided also in socio-economic regions. Guanacaste is part of the Chorotega Region whose extension includes not only the districts of Guanacaste but also the Upala's canton as part of the Alajuela province.

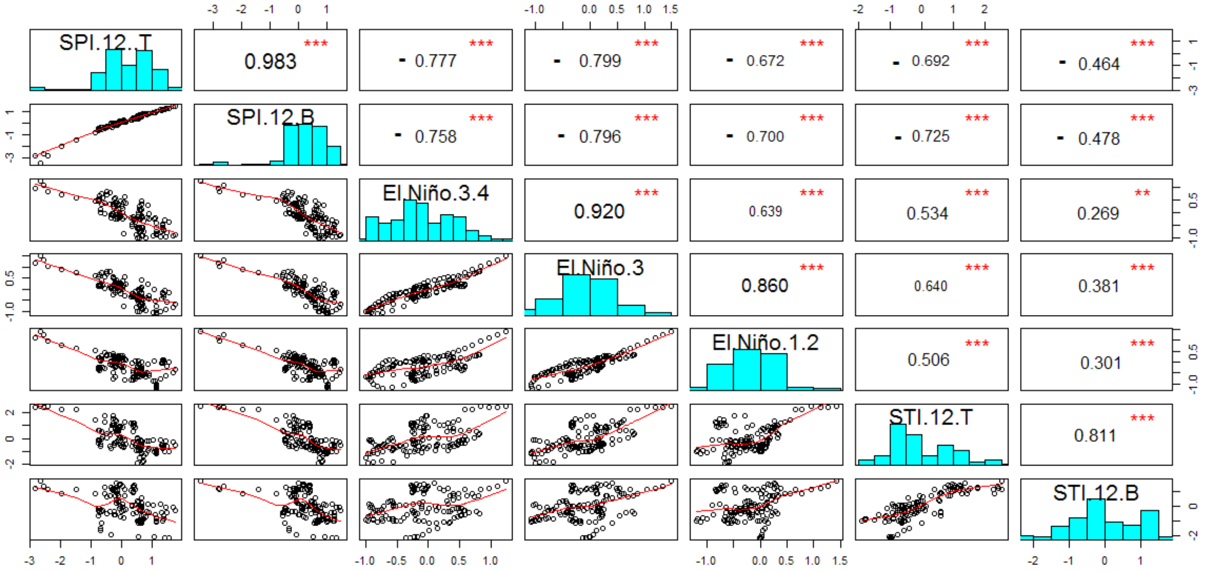

Figure 30 Pearson correlation matrix for Tempisque (T) and Bebedero (B): 1980-2016

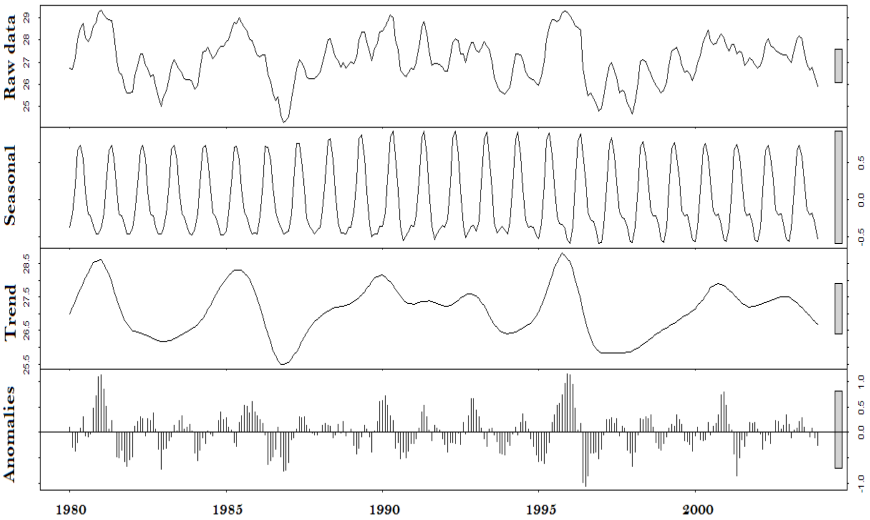

Figure 31 Temporal behavior of ENSO phenomena during the period 1980-2003

The ENSO phenomena during the period of 1980-2003 had important episodes of El Niño which affected rice yield led by the increment of the temperature in the ocean provoking changes in the rainfall regime; figure 29 shows correlation values between annual rice yield anomalies and ENSO indices, as seen the correlation between El Niño 3.4 and rice yield anomalies are about negative 0.30 to 0.37, indicating that the increase in Sea Surface Temperature will lead a decrease in Rice yield.

The effects on rice productivity can be expressed also in percentage of yield variation, which allows perceiving with a better sensitivity the magnitude of these existing variations, especially during water scarcity periods. The following chart (Figure 31) describes the periods in which La Niña and El Niño phenomena were active. The events are classified by categories based on intensity values.

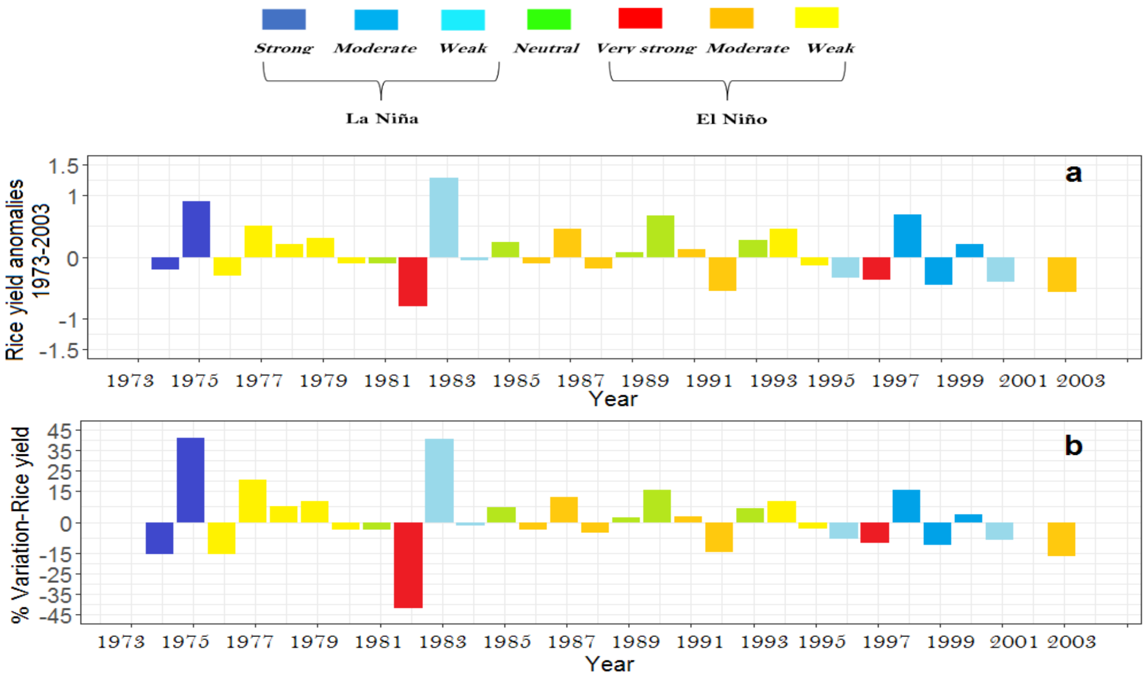

Figure 32 Annual Rice yield anomalies (a) and percentage of variation (b)

5.8. Mete

5.8.1. Temporal and spatial distribution of drought events

As it was not possible to compare trends beyond 2003 using streamflow data to detect hydrological drought periods, in this part of the research an analysis between SPI, STI, SST and rice yield anomalies was made to study trends based on temporal and spatial behaviors and predict future scenarios in the rice sector to encourage the development of tools to mitigate the impacts during periods of water scarcity in rainfed and irrigated zones. In the following figures are represented:

- Temporal distribution of drought periods at multiple time scales (32),
- temporal behavior among SPI-12, SST Anomaly, Temperature anomalies[3] and annual rice yield for Tempisque (a-i) and Bebedero (a-ii) and the years in which ENSO phenomena coincided with negative or positive impacts on rice productivity (33).
- Spatial distribution of meteorological drought for the years 2009 and 2015[4] (34)
- Pearson correlation coefficients among SPI, STI and SST El Niño 3.4 (35)

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[3] Temperature time series were obtained from Terra MODIS dataset provided by Zhengming (2015)

[4] To complete 2015-2016 rainfall data CHIRPS InfraRed product was used. It incorporates 0.05° resolution satellite imagery with in-situ station data to create gridded rainfall time series for trend analysis and seasonal drought monitoring; this information is available to the public starting in 1981 to near present; (Funk et al..,2015)

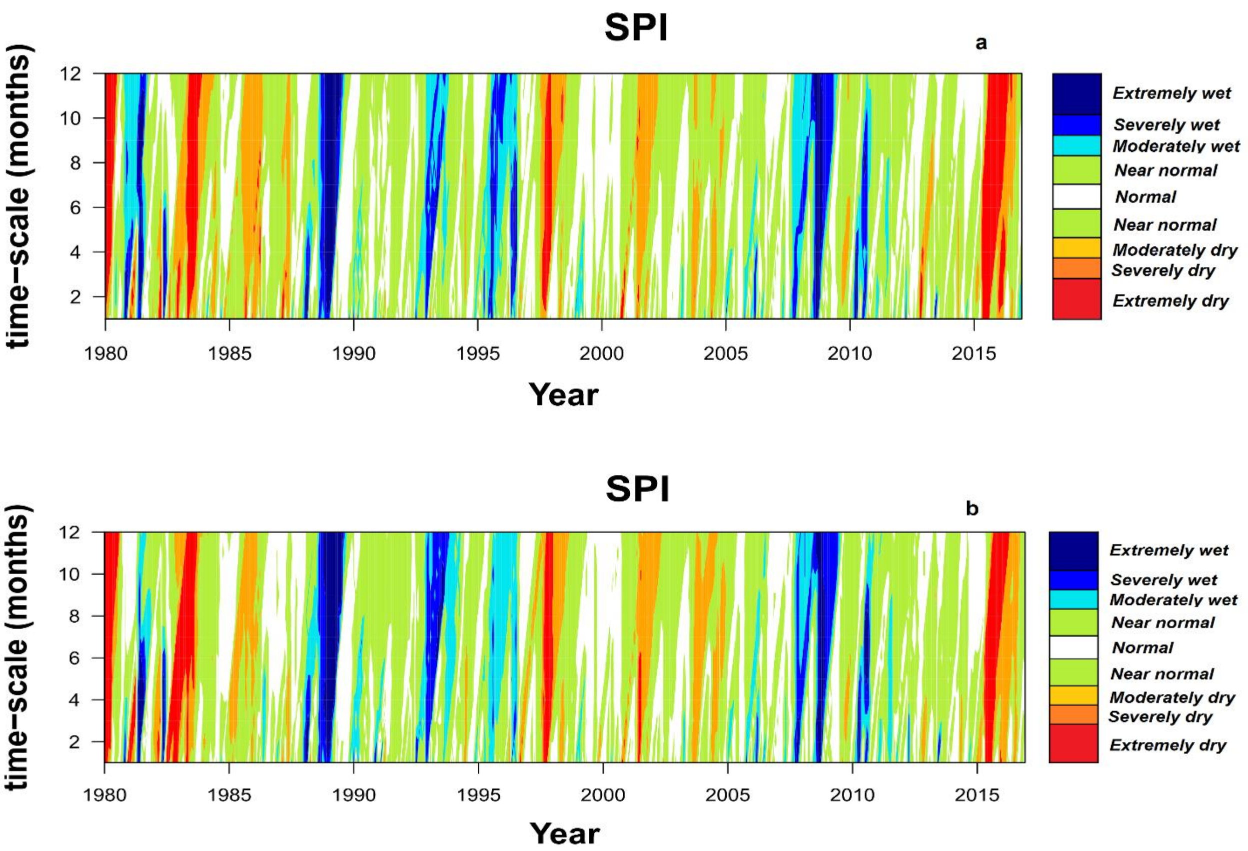

Figure 33 Temporal distribution of meteorological drought at multiple time scales in Bebedero (a) and Tempisque (b)

The temporal distribution of meteorological drought (SPI_{RT} and SPI_{RB}) from 2004 until 2016 showed similar temporal behaviors in some periods in both sub-basins (Figure 32); as described in the multiple time scale chart there were three relevant drought periods in: 2009, 2015 and 2016, in which can notice that 2015 was one of the strongest drought periods experienced in both areas furthermore, they had the same duration but different intensity, this variation is evident at all time scales, moreover, the differences between values that fell into extreme category in Bebedero and those that fell into severely dry category in Tempisque during the same period were experienced during February and March of 2016.

The results show that rice yield had 6 periods in which the productivity was affected (Figure 33 c); some of them associated with climate variability influenced by regional atmospheric circulation patterns (ITCZ) and ENSO phases such as in 2004-2005 and 2015-2016 periods dominated by El Niño and 2007, 2010-2012 by La Niña.

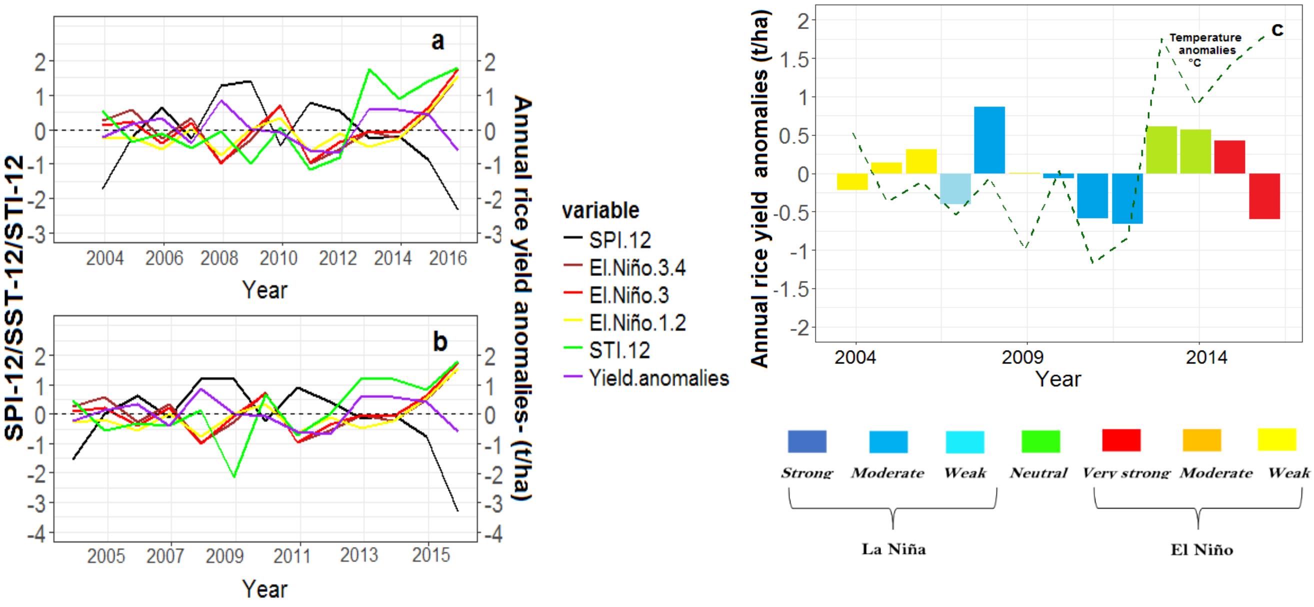

Figure 34 Representation of meteorological drought index (SPI), SST-El Niño 3.4 index, Temperature anomalies and Rice yield for Tempisque (a) and Bebedero (b) and Rice yield anomaly visualization compared with SST-El Niño 3.4 (c)

Part of 2012 was considered a dry year and was linked to El Niño in the region 1+2 starting in February until September, reaching its highest intensity in June of 2012 (Near-normal category); during this year rice yield decreased and there is no evidence of its relationship with ENSO neither precipitation anomalies whose values were below average but classified as near-normal dry period.

On the other hand, meteorological drought during 2015 started in November of 2014 keeping a weak intensity until April of 2015 and reaching a severely dry condition in May, period in which is expected the starting of rainy season; this trend kept constant until October at 3-month SPI, apparently reflecting a poor soil moisture condition affecting great part of crops in Guanacaste as can be observed in rice yield anomalies chart (Figure 33 c) with a considerable reduction and a historical record of the highest temperature deviation.

The visualization of spatial distribution during 2009 and 2015 (Figure 34) was interpolated for July, month in which was registered one of the highest rainfall variations; as result, during 2009 as long time scale was increasing the intensity category was decreasing until developing a near-normal drought; at least for a big part of the catchment, the only exception was presented in the south-east (Bebedero sub-basin), due to drought was more intense at 6-month SPI than at 3-month SPI; at 12-month SPI a small part located at the highest altitudes in the north-east displayed an extremely wet intensity.

In 2015 occurred a similar situation in Tempisque and part of Bebedero that exhibited at all time scales a decreasing gradient but with a significant variation at 12-month SPI at the north-east of the catchment showing an extremely dry condition in the highest parts and moderate dry intensity at the lowest; this trend can be useful to predict a possible behavior of streamflow during this period based on topographical characteristics in the catchment and its capacity to capture runoff water provoking severe hydrological droughts at medium and long-term.

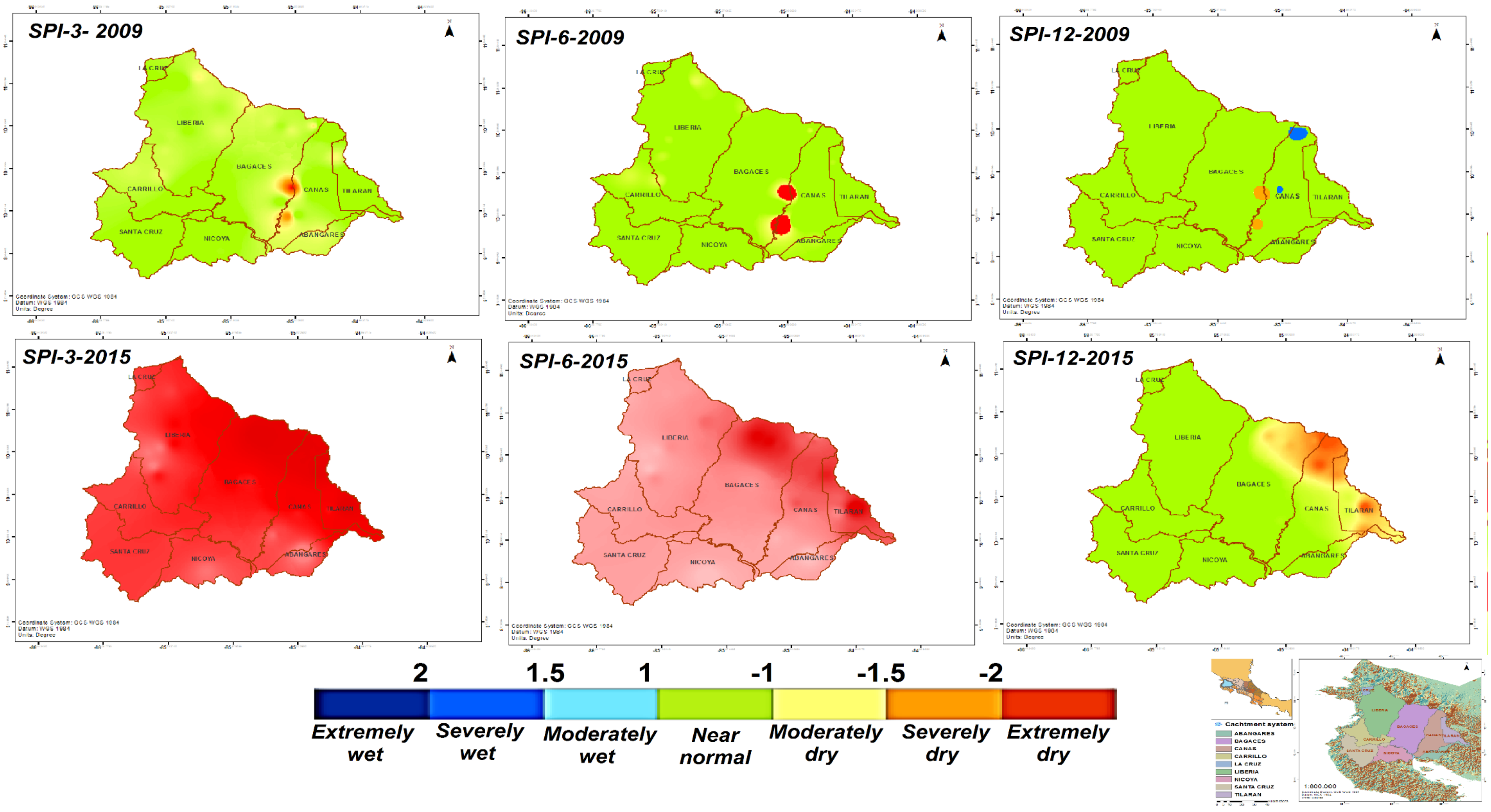

Figure 35 Spatial distribution of meteorological drought: Extreme events for the years 2009 and 2015- month: July

5.8.2. Correlation coefficients

The influence of ENSO, temperature and precipitation patterns on temporal rice yield behavior were analyzed based on correlation coefficients as shown in figure 35, however, as it may be observed, the values exhibited an opposite result for the period 1980-2003 as shown in figure 29; rice yield had a higher correlation with El Niño 3.4 index, while in the second period analyzed (*2004-2016*), correlation coefficient among SST anomaly indices was higher for El Niño 1+2, as well for SPI. As could be noticed, correlation coefficients do not exceed +/-0.4 and this is because the rice yield behavior, not only depends on weather factors and not always have the same response in terms of magnitude when exists a deficit on precipitation or when an anomaly in SST is present; this should be considered because, in some periods in which drought was stronger than other years, rice yield had a non-significative variation (*e.g. 2015-2016*) compared with periods in which yield anomalies were greater than expected during moderate-weak drought events (*e.g. 2003-2004*).

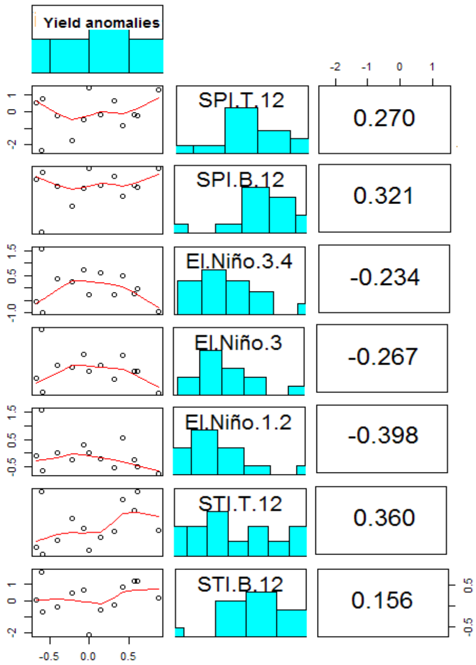

Figure 36 Pearson correlation coefficients among Rice yield anomalies, SPI-12, SST- and STI (Temperature anomalies)-Period:2004-2016

5.8.3. The rice sector during 2009 and 2015

During 2009 and 2015 precipitation dropped causing some effects on agriculture, especially during 2015 which coincided with ENSO phenomena and as consequence left negative impacts on rice sector. In table 20 are summarized the main effects presented in each period.

Table 20 Effects on rice crop during two meteorological drought periods in 2009 and 2015

2009	2015
The rice production slightly increased by 5.10% in comparison with the previous year, Chorotega[2] region contributed with at least 52.86% of the whole national production. During 2009 only 30.67% of the total area was insured (Arroyo Blanco, Lücke, & Rivera, 2013).	The reduction of rice production for the period 2015-2016 was of -13.15%, being one of the lowest during the last 10 years During this period, the region contributed at least 53.7% of the national rice production mostly without irrigation
At least 39.76% of the sowing area was made using PALMAR 18 seed variety, 34.26% PUITA INTA.	The INS reported at least 11537 ha insured which represents only the 23.3% of the total crop area. However, in January of 2016, the INS suspended the insurance service for rainfed rice crop as a result of millionaire losses presented since 2012 above ₡4.141 in total (Brenes, 2016).

Based on: (Conarroz, 2010, Conarroz, 2016)

A big part of the sowing area was under irrigation, most of them belong to large-scale farmers. Since 2007, during both periods were used in great percentage two types of varieties: PALMAR 18 and PUITA INTA CL (Arroyo Blanco et al., 2013) which have a less-longer flowering stage and better yield results. As follows in figure 36 is represented the sowing calendar established for rice crops in Chorotega region.

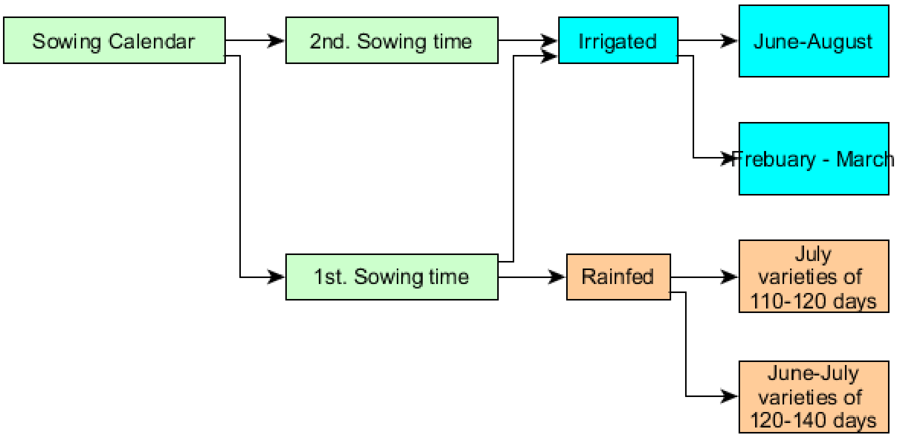

Figure 37 Rice crop: Sowing calendar
Elaborated by the author based on: (Enríquez, 1994)

5.8.3.1. Actions taken by stakeholders to mitigate agriculture impacts

In March of 2009, The Ministry of Agriculture and Livestock (MAG) transferred to the INS ₡1000 million to subsidize crop insurance, this investment covered the 50% of the insurance contract only for farmers with sowing areas between 1 and 50 ha. This initiative was part of the National Food Plan promoted by the Government (Agüero, 2009).

In 2015 the National commission of risk prevention and emergency attention declared yellow warning moved by the high deficit on rainfall pattern presented during the rainy season; this calling of emergency was decreed for 19 cantons part of them located in Guanacaste province which presented during September a reduction in precipitation of 53% (Martínez & Quirós, 2015) according to IMN reports based on ENSO indices.

Since 2011, the Ministry of Agriculture and Livestock in conjunction with the IMN and SEPSA have worked in different strategies to mitigate and prevent the effects of climate change in different regions. The IMN is in charge to emit quarterly reports over climate scenarios and precipitation forecasting to prevent socioeconomic impacts. Moreover, the SEPSA organized regional workshops centralized on use of water to strengthen the coping capacity of the community during climate extreme periods (Quirós, 2014).

As part of one of the strategies proposed by the MINAE, the prohibition of well drilling was one of the most important points to avoid overexploitation of water reservoirs principally in water scarcity periods. The objective of the decree was to give priority to the use of water for human consumption in the most affected cantons (Liberia, Nicoya, Santa Cruz, Bagaces, Carrillo, Cañas, Abangares, Tilarán, Nandayure, La Cruz) and to regulate the demand of water through the use of streamflow meters (Garcia, 2016)

6. DISCUSSION

6.1. Filling of Rainfall data using satellite imagery

The correlation coefficients between satellite measurements and land observed data for precipitation, were above 0.8 in most cases, indicating that this product is suitable to complete gaps in rainfall data sets since it is a spatial-interpolated and cross validated product and moreover, has a good spatial-temporal resolution with a complete coverage in the study area. This type of products with availability to the public were an important tool for the development of this research considering that some gaps in rainfall data can lead statistical limitations and less confidence depending on the method of calculation (WMO, 2012). As recommended by Githungo et al. (2016), the use of remotely senses rainfall estimates might lead errors due to the space-time differences, for that reason it is important to select suitable products with a good temporal and spatial resolution based on the characteristics of the study area.

As follows will be discussed the strengths and weaknesses of the research carried out in the assessment of meteorological and hydrological drought and their impact on rice yield in the study area.

6.2. Meteorological drought

Tempisque and Bebedero watersheds have similar climatic conditions; however, the few differences between them in terms of basin area, topography and, precipitation regimes might explain the results obtained in the meteorological drought characterization in which was observed more frequent drought events in Bebedero than in Tempisque but with a lower duration; additionally, to the higher number of droughts experimented in the category of mild drought and the highest duration at 12-month time scale in the extreme category, whose results coincide with previous researches developed in the study area as reported by Patterson (1992) in which were found by applying the Palmer Drought Index in the province a 32% of mild-drought events, 11% categorized as severe and only 3% as extreme drought. The research also indicated that May, July, and August are months in which drought has its onset.

On the other hand, one of the most important achievements in the study of the characterization of meteorological drought in this research was the availability of dataset provided by the IMN; despite the fact of existing incomplete time series, the number of meteorological stations in the area allowed to represent by interpolation the spatial distribution of drought periods, especially the most extreme periods developed in the region to be able to analyze the most impacted areas and establish the presence of spatial trends.

As described by Cui et al. (2016) in their research focus on Monitoring Drought and Water Balance in the Guanacaste Province, the spatial distribution of SPI showed the same results as presented in this thesis; apparently exist marked differences of drought conditions in the western and southern part of the catchment system in comparison with Easter and Northern zone as result of climate characteristics, in this research this trend was more evident during extreme drought periods at different time scales.

6.4. Hydrological drought

One of the weaknesses in the development of hydrological drought index was the limited data set regarding temporal and spatial coverage; for this research, only two stations with a complete dataset were used. Apparently, this information is not open to the public which reduces the relevance in the study of temporal streamflow variability across the catchment system, especially because the time series go until 2003 with more than 14 years without information; according to MINAE, Guardia streamflow gauge operated until 2010, later, the Dirección de Aguas decided to manually measure the flow of the basin, but there are not official reports of the recorded data.

The hydrological drought periods developed throughout the catchment showed relevant information over temporal distribution and main differences between watersheds understood from their characteristics in flow regime, climate, hydrogeology and, topography. In the eastern part of the Northern zone where developed significant droughts with higher severity than in the western, which reveal a higher susceptibility to exposure of extreme droughts mainly during the rainy season, this behavior was also reported by Birkel (July/2005) in a research focused on temporal and spatial variability of drought indices in Costa Rica; the author reported the same trend in terms of less frequency of drought events in the eastern combined with more severe droughts, furthermore, explains that part of the droughts developed across the North zone might be understood by physical characteristics and storage capacities of the watersheds.

The volume deficits presented in the region calculated from the FDC and THLM selection represents an important tool to define drought events due to the strong seasonality in flow regimes existing in the catchment system; the given discharge just represent the values in which should not be exceeded for a specific period and season. The values of volume deficits at short-term were more severe in the eastern zone using a seasonal constant threshold Q_{70} based on the literature referring to Costa Rica climatic conditions (Birkel, July/2005) considering that a constant seasonal Q_{70} percentile reflects a better sensitivity during both seasons more than a Q_{90} percentile which not detects remarkable deviations during the rainy season. With the application of this method was clearly revealed the strong seasonality in the area during the high flow season and low flow season, and this could be interesting to compare with monthly time series regarding water supply to analyze the situation of water management issues during the period analyzed.

6.5. Meteorological and hydrological drought correlation

The response of precipitation on streamflow regimes is not given immediately for that reason is expected a lag on the effects of precipitation variability on streamflow behavior. Notably, for this research was observed a significant correlation from 1980 to 1989, however, since 05.1989 this correlation was non-significant, especially until 07.1995. According to Westerberg et al. (2014) in a research based on regional water balance modeling using flow-duration curves, precipitation data seemed inconsistent when inspecting the time series with discharge values resulting in a low correlation between them. These results were also reported by Gónzalez, Jímenez, & Pizarro (2005) in which was determined a non-correlation between precipitation and streamflow data during 1980-1999 ($p < 0.05$) apparently, according to the author as a response to water withdrawal for irrigation and human consumption purposes.

Based on the above, these widely nonproportional situations can be explained by:

1. Land use changes: In spite, there are not public documentation in relation to main changes produced in land use year by year caused by anthropogenic activities, certainly, exists a probability to consider a decreasing of surface runoff by

changes in vegetation cover (changing on type of vegetation, altering soil properties) inhibiting thus the percolation process and reducing groundwater levels. Also, the topography has a significant influence on runoff rates in both sub-basin by cause of little slope which is between of 5% and 15% (Ginneken & Calderón, 1978, 1978). This condition is more evident in Tempisque than in Bebedero.

2. Amount of streamflow granted: during this period, there are no official reports with public access regarding to monthly streamflow granted for each activity, however, based on general information for the whole country from 1985 to 2008; since 1992 there was a significant increasing of the 60.47% on the number of permissions granted for water extraction, whereas in 1994 the increase was more than 92% until 1997, during this period due to El Niño phenomenon the number of new streamflow grants was plummeted (Adamson-Badilla, Marcos, & Masís, February/2010). These statistics are relevant considering that Tempisque is the third river-basin with the greatest number of water wells used for pumping purposes.

   In 1991 the 75% of surface water was used for agriculture purposes (Gómez, Rodríguez, & Losilla, 1991); and as shown in recent reports emitted by the Dirección de Aguas de Costa Rica the percentage of total streamflow for irrigation purposes has kept steady, probably because most of the industries with the highest amount of streamflow granted have a pumping license since 1970.

This information supports the results obtained in the correlation between SPI and SDI indices considering the low correlation coefficients obtained for some stations (α=0.01) at 3, 6 and 12-month time scales. Additionally, it is important to highlight that hydrological drought depends on many factors, not only is affected by the rainfall pattern variation, but also on the temperature which has an important function in water loss by evaporation; moreover, the distribution of rainfall on the surface of the basin, its direction, vegetation cover, runoff, and infiltration capacity are relevant variables to explain changes in streamflow regime in the basin; in addition to the water extractions that are made at the surface and underground level.

6.6. *Drought, ENSO and Rice yield relationship*

El Niño 3.4 is widely used to monitor Pacific Ocean temperature anomalies, this international and primary standard is used to declare a warning based on SST index, these anomalies presented in this region of the Pacific Ocean can provide an important prediction of regions 3, 4 and 1+2 which might have a direct influence in Costa Rican climate pattern. Particularly, in this research were revealed significant negative correlations between SPI and Sea Surface Temperature indices, especially in the region 1+2 ($\alpha=0.001$), this maximum correlation was observed for the time lag zero, and it coincides with Steyn, Moisseeva, Harari, & Welch (2016) concluding that ENSO phases have an effect on precipitation in Guanacaste with high correlations, however there is no evidence of time trends to be revealed. Additionally, other authors such as and Enfield & Alfaro (1999) and Caviedes, Quesada, & Waylen (1996) found the same trend across Costa Rica; nevertheless, in terms of hydrological drought Birkel & Demuth (2006) found moderate correlations at an inter-seasonal scale mainly during the high flow season which is consistent with the results obtained in this thesis.

In contrast, the response of rice yield on rainfall and discharge variability showed a lower correlation especially in Bebedero (r=0.328; r=0.207). In terms of magnitude; apparently there is not a proportional relationship between streamflow and precipitation anomalies mainly during extremely prolonged periods; however, some authors have reported decreasing on precipitation associated with El Niño event which has produced agricultural losses of rice crop principally during the rainy season, period in which rainfed crop is sown (Retana, Villalobos, Alvarado, Sanabria, & Córdoba, 2014). According to a research developed by the IMN (Villalobos & Retana, 2000) based on a comparative assessment of agricultural uses of ENSO Important drops in precipitation were presented mostly in July and August (Mid-summer drought), but the highest deficits were during the rainy season in months in which is expected the peak in rainfall, coinciding with the results showed in the assessment of meteorological and hydrological drought given in this thesis.

As can been seen, one of the limitations in the correlation assessment to demonstrate the influence of SPI, SDI and SST on rice yield was the lack of enough data and the spatial distribution of rice farms to analyze the impacts produced across the catchment system. Currently there is no monthly recorded data per district or province, only some estimations for the whole country, nonetheless, as long as Chorotega region is the biggest producer of this basic grain, can be said that is feasible to estimate some correlations on the basis of annual rice yield data in Costa Rica, after all it is important to keep in mind that some errors must be considered because there is not a clear separation on seasonal performance on area and production in the study area, concluding in a low sensitivity in the detection of impacts caused during each sowing period.

By last, it is important to consider that not all years in which ENSO warm phase (El Niño) was present provoked an abnormality on rainfall and discharge regimes as well on crop productivity, and this can be explained by:

1. Variability on climate can be influenced by ENSO events but the regional response depends also on catchment's characteristics such as topography.
2. Crop yield depends not only on weather, but also on variety of seed used and its coping capacity to periods of water scarcity, fertilizers, soil moisture, farming techniques, sowing date, temperature, irrigation, use of pesticides etc., based on literature review, there are many factors which are not feasible to estimate and sometimes they result insignificant, others have an important impact such as soil moisture but its measurement is not common as precipitation is (Boken, Cracknell, & Heathcote, 2005).

6.7. Impacts on Rice yield during 2004-2016 and its correlation with SPI, Temperature anomalies, and ENSO indices

6.7.1. Analysis of temporal rice yield behavior

The performance of rice yield from 2004 to 2016 had the same temporal behavior as the one analyzed for the period 1973-2003, however, particularly for the last period some of the drought events were documented by Esquivel et al. (2012; Decreto: 36252-MP: Emergencia nacional por afectación de sistema de baja presión, 2010) as part of the National commission of risk prevention and emergency attention and Bonilla V & Brenes (2013) as part of a study case based on disaster and risk reduction supported by the UNISDR, in which were studied the impacts produced by ENSO phenomena such as the case of 2010-2012 whose episode reached the most intense phase in June of 2010 and May of 2011 followed by a neutral period and keeping again a high intensity in August of 2011 (flowering period in which water availability is needed) until 2012 with a moderate intensity; It is worth highlighting that during this is period the increment of rainfall in the North Pacific reported by the last author, specifically in Guanacaste was around of 110% in the upper-basin and 65% in the low-basin, this increment on rainfall led a decreasing on yield, mostly because during some phenological stages of rice development the excess of water can produce damages in the plant, but this is only caused depending on the severity and duration of the event. Additionally, as reported on decree 38642-MP-MAG: Estado de emergencia la situación generada por la sequía - Fenomenó del Niño - ENOS (2014) emitted by the National commission of risk prevention and emergency attention, 2015 was declared as a drought year with a strong intensity (One of the strongest presented in Costa Rica), this result was also reported in this research. Internationally El Niño Anomaly 3.4 index registered its onset in October of 2014 with a weak intensity, but only until July of 2015 became moderate intensity provoking a strong inter-seasonal variation.

Considering above information, drought onset and termination constitute an important data to analyze rice behavior based on sowing calendar and water requirements due to sometimes the lack of this resource does not have a significant impact on productivity especially in dates in which the plant does not need a high amount of water for its growth and development.

6.7.2. Correlation analysis

In terms of correlation analysis, similar results as presented in this thesis in which apparently rice yield was not affected by precipitation and SST anomalies were found by different authors with the addition of official documentation to explain crop deficits; as an example, during the period of 2003-2004 as was reported by CONARROZ a plague known as Steneotarsonemus spinki acarus entered in the country in 2003 but only until May of 2004 was identified in Guanacaste, Panamá and Nicaragua (Servicio fitosanitario del estado, May-June/2005). This plague caused a decreasing in the quality and quantity of grain produced. Agricultural losses were around 40.000 tons of rice in the whole country (La Nación, 2004). Furthermore, during this year the INS emitted a normative in which where established that crops attacked by Steneotarsonemus spink would not be covered by the insurance. A similar situation occurred in 2009-2010, which can explain the low yield presented not only led to weather conditions but also by plagues disseminated in the area; in this particular case based on a scientific research elaborated by Garcia & Quesada (2014) a bacteria (Burkholderia glumae) which reduces foliage growth causing plant wilt, was found in the 49% of the analyzed seeds during 2009 and 44%. in 2010. In spite, there are no official statistics about how many hectares were affected by the pathogen, it could be an important variable to understand the high anomaly on rice yield during this period.

Although there is a need to implement an organized and classified database on crop monitoring, Costa Rica does not have one, at least not with access to the public that allows to support or explain the anomalies of rice behavior considering that climate condition is not the only variable that affects rice performance.

6.8. How Guanacaste face drought events and impacts in the Agricultural sector?

Guanacaste as part of the Chorotega region is highly prone to drought events, for that reason Costa Rican government emitted the decree Nº 40453: Acciones para la atención de la gestión sostenible de agua ante la sequía y acceso a aguas a las poblaciones y producción en la vertiente Pacífico Norte (2017) by which it pretends to give priority to the use of water for human consumption and economic development in a sustainable scenario of water management and protection of the environment. The normative establishes the commitment in the technical and legal evaluation on the request of drilling wells in the region based on water supply and water demand requested by the applicant; specifically, for the agricultural sector administered by the National Groundwater, Irrigation and Drainage Service (SENARA) in coordination with the Ministry of Agriculture and Livestock and the Water department of MINAE.

Since 1974 the government through the project of irrigation Arenal-Tempisque has implemented solutions to provide irrigation to farmers and promote the agricultural development by the transformation of an extensive rainfed agriculture to an intensive irrigated agriculture in the districts located at the low-basin using water resources from the Arenal-Reservoir/lake (SENARA, 2017). This initiative is relevant considering that rainfed rice crop is highly dependent on rainfall and especially because most of the number of rice farms located in the area do not implement irrigation techniques probably because of high costs and difficulties of water access (See section); however, the project only covers a small part of Guanacaste and based on the latest statistical agriculture census developed by the INEC (2014a), only the 3.98%[5] are benefited with the Arenal project.

On the other hand, despite the fact that farmers have the possibility to acquire a crop insurance in the INS and access easily to credit banks to improve their agricultural techniques, only a few percentage has the opportunity to get one, mainly because the number of beneficiaries has decreased since drought events became more frequent in the region (figure 14) by which it makes more difficult to recover economic losses occasioned by drought events (more information: Crop insurances in Guanacaste), becoming the sector more vulnerable in terms of sensitivity and coping capacity to extreme meteorological events.

It is worth recognizing the work of the National Meteorological Institute (IMN) in matters of prevention of hazards produced by extreme meteorological events, since 2011 through the Commission of ENSO phenomena (COENOS) the IMN has been elaborating every fifteen days monitoring reports that later are uploaded on its website; This information is also shared in press releases and on the official websites of the Executive secretary of agricultural sectoral planning (SEPSA) and from this update, the National commission of risk prevention and emergency attention is in total authority to declare alerts to take the respective measures. This initiative to monitor climate variability is highly relevant due to as was reported in this thesis (figure 36) as well by Retana (2001), atmospheric circulation patterns (Global and regional) and SST anomalies have a significant influence on climate in the region. During the period 1980-2016, precipitation and temperature anomalies showed an important correlation with SST anomalies in all the regions, especially in the region 3 with a significance level of 0.001, so it means that the function of periodic reports should continue to be implemented as a prevention tool to take actions against negative impacts of climate change.

6.9. Decision makers: Public Institutions

In Costa Rica exists many public institutions in charge of water management issues, all of them are regulated by the Law of Water (N°276: Ley de Aguas,1942) promulgated in 1942; the Law has been modified in some of its articles but it continues being obsolete considering that the population of the country has grown as well as the demand of water. After more than 25 proposals presented since 2001

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[5] This percentage was calculated fro the total existing farms in Guanacaste (Regardless of their productive activity). There are not recent statistics of how many rice farms are being benefied by Arenal-Tempisque Project.

by a popular initiative to change the law for an integrated management of water resources law in which can be organized the current complex system in charge of water regulations, until today it continues being evaluated by the legislative assembly.

As reported by Zeledón (2015) director of the water department in Costa Rica at a conference in Chile, the new proposal pretends to regulate water use regarding to streamflow granted (Extension of licenses), environmental streamflow and Intervention during periods in which streamflow is reduced, etc., variables than until today are not considering at the time to emit licenses for water extraction. As shown in table [16], for the period 1980-2003 was calculated the seasonal threshold values which represent the percentage of time that a given flow rate of the stream was equalled or exceeded; this information would have been more useful in terms of water management in the analysis of temporal behavior on water demand by streamflow granted for different activities developed across the basin if public available data of monthly discharge would had been existed and also, type of resource used for water supply (surface water, groundwater...etc.,) to compare, analyze or calculate the periods in which the volume of water was exceeded in each activity.

One of the biggest obstacles at institutional level in Costa Rica is the lack of organization and access to information. As described in this thesis, only was possible to work with streamflow data of two stations (table 9); despite the fact that the amount of water is studied and granted by the Ministry of environment and energy of Costa Rica based on water supply balance reports and controlled by the department of water, apparently, exists a controversy in terms of monitoring due to there were only two streamflow stations operated by the ICE (Costa Rican Institute of Electricity) until 2010 (MINAE, 2016); it means that the lack of monitoring system in the basin has not allowed controlling whether an over-grant of water is present.

6.9.1. Status of water demand for irrigation

The following information in matters of streamflow granted categorized by water resource was downloaded from the department of water web site (Dirección de Agua, 2017); in this platform is updating periodical information about:

- ✓ Flow assigned by activity (by basin, district, number of farm etc.)

- ✓ Flow granted by basin, district, by name of the applicant
- ✓ Information by basin (Flow granted L/s)

As is described in the following figure [38], both watersheds use ground water reservoir and surface water for irrigation purposes, however, most of the area does not implement irrigated agriculture and only a part of the low-basin is provided by the Arenal-Tempisque project.

In the maps, can be noticed that in Tempisque is most common or frequent the use of groundwater than in Bebedero [b and e]; nevertheless, if it is compared with the amount of surface water granted for irrigation, both areas use more this source of water for this activity.

Tempisque has a higher demand for water than in Bebedero, especially for irrigation purposes and considering that most of its activities are developed at the middle-basin, this region becomes more prone to greater impacts produced by prolonged drought periods; this type of vulnerability by exposure can be expressed also considering the amount of water granted and the available discharge in each point. In figure [c and f] are represented the areas in which the amount of flow granted has exceeded the available discharge becoming the area more exposed to bigger impacts.

Currently, the department of water in Costa Rica has been monitoring pumping system of each authorized point for water extraction in the Tempisque river, in some of them, there is no control of the amount of water pumped (Martínez, Pérez, & Solano, 2017), what it makes impossible to determine if exists an over demand above of the allowed volume.

Additionally, it is important to mention that exist illegal extractions of water which were not taken into consideration in this research because of lack of information and whose functionality affects the water resources of the area, however this is only a response to the weak regulation that exists in the current water law since does not penalize the drilling of illegal wells.

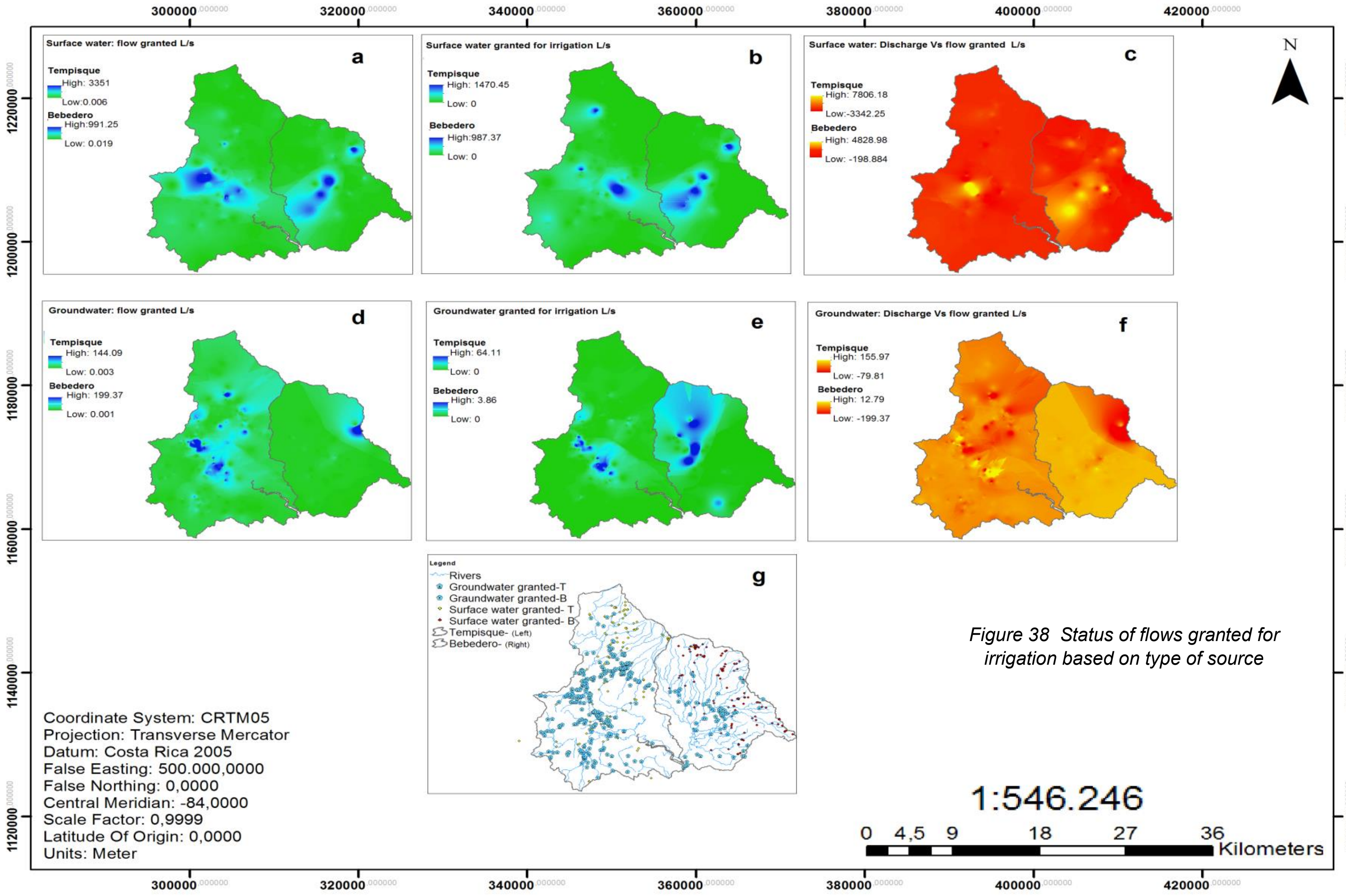

Figure 38 Status of flows granted for irrigation based on type of source

7. CONCLUSIONS

This thesis research assessed meteorological and hydrological droughts in the Tempisque-Bebedero catchment system by using SPI and SDI criterion, which were analyzed with annual rice yield data to establish the correlation level between drought periods and temporal behavior of this crop. It has been found that Tempisque watershed presented more extreme droughts in terms of duration but with a low frequency contrasted with Bebedero; however, this difference is not enough wide to conclude that they have completely different temporal behaviors.

In terms of spatial distribution, both watersheds showed significant differences especially associated with their topography and storage capacity in the upper-basin side; during extreme drought periods at 12 months-SPI in which are reflected long-term precipitation patterns and tied to streamflow, reservoir levels, and also groundwater levels shortfalls, Bebedero exhibited most extreme periods than Tempisque probably justified by its low permeability due to geological characteristics that allow a slow movement of water; which indicates that particularly this region of the catchment system is more susceptible to droughts influenced by natural variations of the hydrological cycle.

The temporal distribution of hydrological drought for the period 1980-2003, showed similar characteristics in both watersheds; during the rainy season were more severe deficit volumes of streamflow than those experienced during the dry season marked by less severe deficits, furthermore, in both watersheds, was evidenced the influence of rainfall anomalies during the rainy season resulting in a later hydrological drought development; in most of the cases in which an extreme o severe event occurred, a prolonged streamflow deficit was developed not only during high flow season but also at low flow season. This behavior is frequent in the region because of its marked seasonality.

Based on correlation test, it can be found a significant influence of SST anomalies on rainfall variability with a high significance level ($\infty=0.001$, $r > 0.7$). These anomalies combined with global and regional circulations patterns are modified by catchment's topography for that reason the effects of the ENSO phenomena had different spatial and temporal behavior across the watersheds.

Based on literature review, climate variability has an influence on crop yield anomalies, however, the correlation test had revealed low correlations values with SPI and SDI indices and rice yield anomalies, and it is because, during most of the periods in which rainfall was below normal rice yield decreased in a lower magnitude, and only during extreme meteorological and hydrological events, rice yield exhibited a proportional decreasing in almost the same magnitude, moreover, in most of the cases in which drought period was presented marked by extreme category, water deficits were most severe during the end of August, September, October, and beginning of November, time in which the plant requires the highest amount of water for its development.

Recommendations

- This research was limited by the available data to study in detail hydrological drought and rice yield anomalies, especially in terms of spatial distribution, for that reason it was not possible to determine a direct impact of rainfall on crop yield by district or cultivation area since there is no information about location and extension in hectares of rice farms. From this point, to predict future scenarios with better accuracy, it is highly recommended to develop a hydrologic simulation model to monitor and assess how the water resources are managed in the area to take actions to prevent and mitigate the impacts of droughts in Guanacaste.
- To improve agricultural techniques and decision making, it is important to incorporate crop models to predict yields based on physiological processes during plant development considering variety of seed used for each sown period and water requirements; furthermore, the SEPSA must continue offering training courses to farmers to promote proper land use, water resources and improve the competitiveness.

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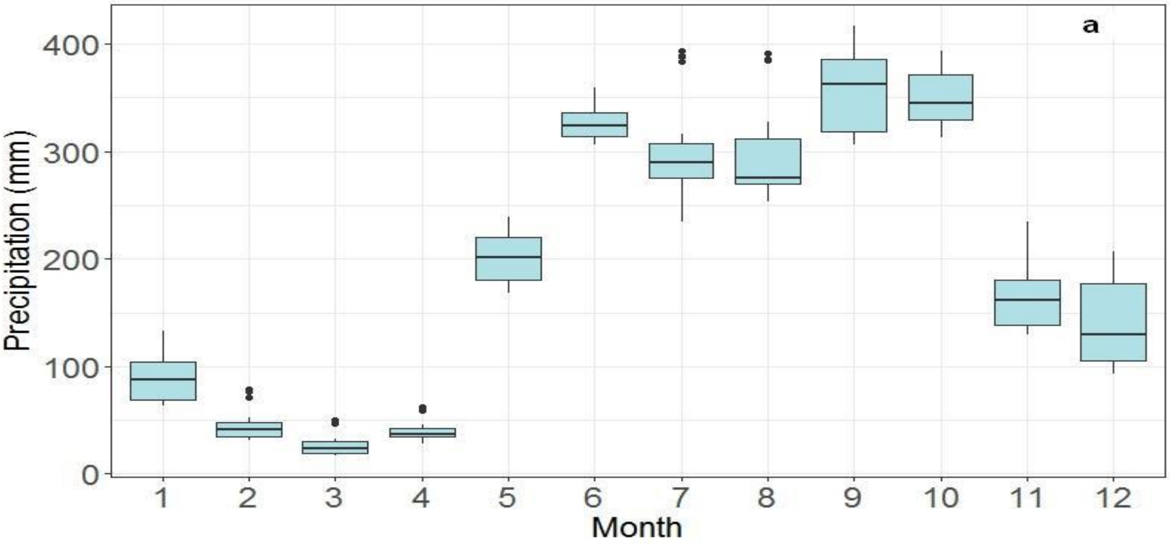
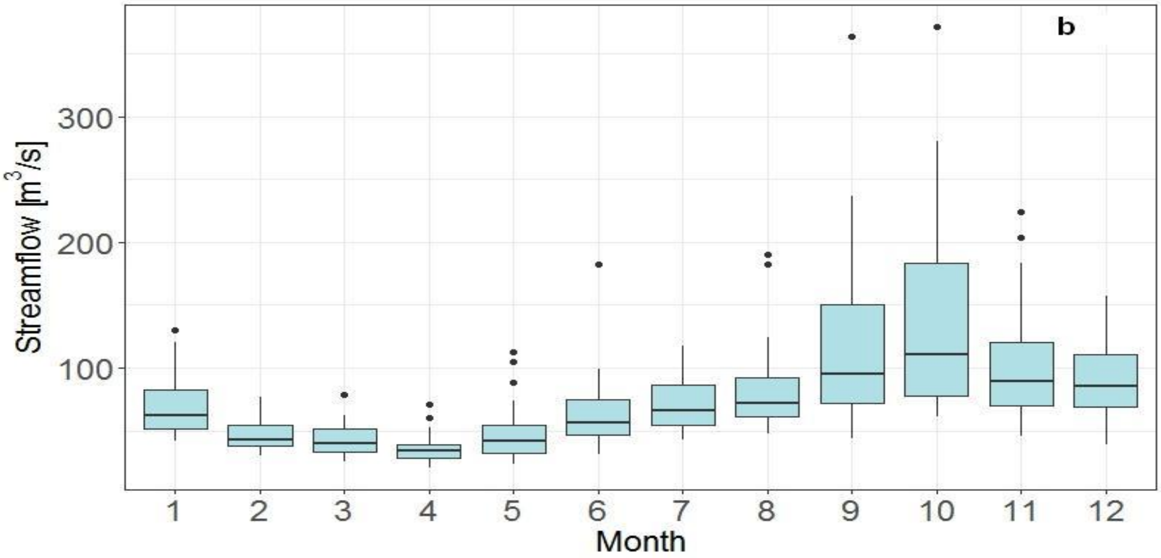
APPENDIX

APPENDIX A

a) Monthly rainfall distribution in Bebedero



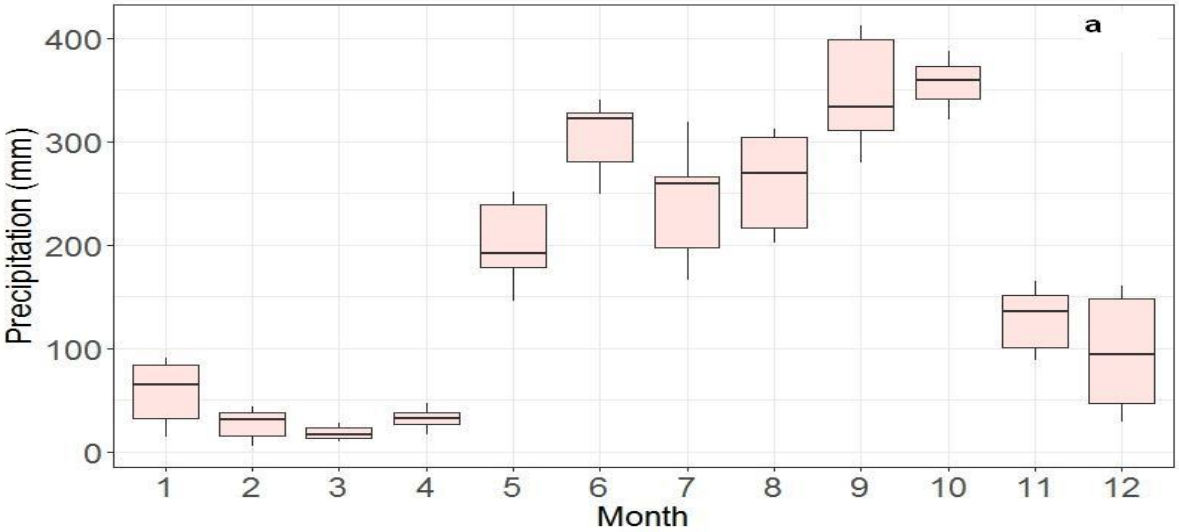
b) Monthly streamflow pattern in Bebedero



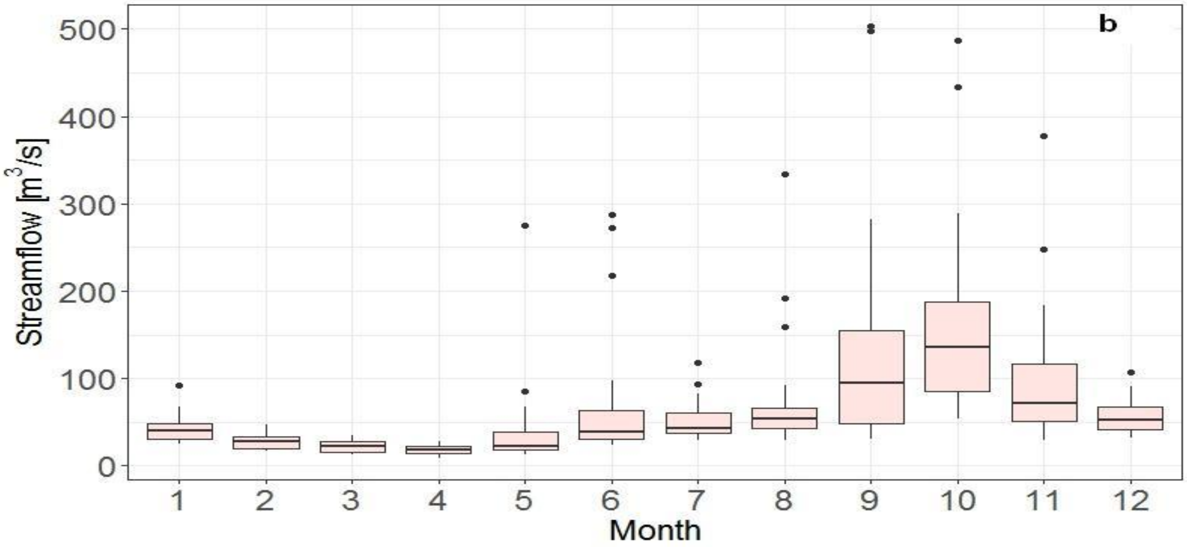
Elaborated by the author based on: (IMN, 1948-2016; Matsuura & Willmott, 1900-2014); rainfall data set completed using NOAA/OAR/ESRL PSD (Matsuura & Willmott, 2012)

APPENDIX B

c) Monthly rainfall distribution in Tempisque



d) Monthly streamflow pattern in Tempisque



Elaborated by the author based on: (IMN, 1948-2016; Matsuura & Willmott, 1900-2014); rainfall data set completed using NOAA/OAR/ESRL PSD (Matsuura & Willmott, 2012)

APPENDIX C

e) *Drought characterization in Tempisque catchment based on SPI at different time scales*.

		Río Tempisque-Río Tempisquito																							
Stations		**Santa Rosa**						**Quebrada Grande**						**Monte Galán**						**Cañas dulces**					
		Time scale						Time scale						Time scale						Time scale					
		3		6		12		3		6		12		3		6		12		3		6		12	
		*E**	*D***	*E*	*D*	*E*	*D*	*E*	*D*	*E*	*D*	*E*	*D*	*E*	*D*	*E*	*D*	*E*	*D*	*E*	*D*	*E*	*D*	*E*	*D*
Threshold	0 to -0.99	115	2,2	109	3,11	95	5,94	85	2,43	84	3,65	71	5,92	104	3,35	95	4,32	109	10,9	77	2,26	85	3,4	76	6,91
	-1.0 to -1.49	18	1,3	26	1,86	32	5,33	16	1,45	16	1,14	22	2,44	14	1,08	22	1,69	12	1,71	28	1,65	21	1,24	28	3,11
	-1.5 to -1.99	4	1,0	3	1	5	1,25	17	1,55	9	1,29	14	2,8	12	1,2	12	1,71	14	3,5	13	1,18	10	1,25	14	2
	-2.0 to less	3	3,0	6	6	9	9	12	1,71	17	3,4	13	6,5	9	1,5	10	2,5	11	11	6	1,2	13	2,6	9	4,5
Max. Duration	months	15		23		38		24		28		39		27		39		51		15		28		42	
	Year	1997		1998		1998		1986		1983		1986		1997		1983		1998		1986		1983		1983	
Min. SPI	Value	3,1		2,97		2,64		3,54		3,97		3,05		4,46		3,44		2,63		3,46		3,65		2,8	
	Year	1997-1998		1997-1998		1997-1998		1985-1987		1985-1987		1985-1987		1996-1998		1996-1999		1996-1999		1982-1983		1982-1984		1982-1984	
Min. Severity	Value	17,33		23,69		27,16		46,34		49,7		51,63		24,45		33,71		41,14		24,99		37,88		37,96	
	Intensity	1,16		1,58		1,94		1,93		1,77		1,99		1,02		0,86		1,14		1,67		1,52		1,52	
Max. Intensity	Year	2003		1997-1998		1997-1998		1985-1987		1985-1987		1985-1987		1980		1996-1999		1996-1999		1982-1983		1982-1984		1982-1984	
	Value	1,15		1,58		1,94		1,93		1,77		1,99		1,36		1,12		1,14		1,67		1,52		1,52	

*: Number of total events per category; **Mean duration per category based on drought periods

		Río los Ahogados											
Stations		Borinquen						Hacienda los Angeles					
		Time scale						**Time scale**					
		3		6		12		3		6		12	
		*E**	*D***	*E*	*D*	*E*	*D*	*E*	*D*	*E*	*D*	*E*	*D*
Threshold	0 to -0.99	87	2,42	84	3,36	75	6,25	103	2,71	72	4	65	7,22
	-1.0 to -1.49	22	1,29	23	1,44	24	2,18	21	1,5	26	2,36	21	3,5
	-1.5 to -1.99	12	1,5	9	1,13	13	2,17	8	1,14	14	2	14	2,8
	-2.0 to less	11	1,83	11	2,75	10	5	9	1,8	11	2,75	13	4,33
Max. Duration	months	15		30		42		29		39		51	
Min. SPI	Year	1983		1983		1983		1997		1997		1998	
	Value	3,85		3,75		2,55		2,95		2,67		2,76	
Min. Severity	Year	1982-1983		1996-1999		2000-2003		1996-1999		2000-2003		1999-2003	
	Value	29,94		30,3		37,23		33,33		46,04		54,1	
	Intensity	2,00		1,08		0,89		1,15		1,18		1,06	
Max. Intensity	Year	1982-1983		1982-1984		1982-1984		1980		1996-1999		1996-1999	
	Value	1,99		1,83		1,24		1,68		1,27		1,41	

*: Number of total events per category; **Mean duration per category based on drought periods

		Río Colorado																	
Stations		**Hacienda Guachilipin**						**Colorado Liberia**						**Hacienda la Flor**					
		Time scale						**Time scale**						**Time scale**					
		3		6		12		3		6		12		3		6		12	
		*E**	*D***	*E*	*D*	*E*	*D*	*E*	*D*	*E*	*D*	*E*	*D*	*E*	*D*	*E*	*D*	*E*	*D*
Threshold	0 to -0.99	87	2,07	86	3,44	75	4,69	67	2,03	91	3,03	93	5,17	102	2,91	92	3,41	104	10,4
	/-1.0 to -1.49	19	1,58	24	1,26	26	2,36	36	1,64	22	1,47	33	3,3	22	1,38	25	1,56	8	1,6
	/-1.5 to -1.99	13	1,3	14	1,56	20	2,22	10	1,11	14	1,56	10	10	8	1,14	10	1,43	17	3,4
	/-2.0 to less	13	1,63	7	1,75	8	2,67	9	1,5	9	2,25	5	5	7	2,33	10	2,5	11	11
Max. Duration	months	15		30		42		15		39		45		27		33		51	
Min. SPI	Year	1982		1984		1998		1985		1980		1983		1997		1998		1998	
	Value	4,05		2,44		2,31		2,8		4,81		2,49		4,39		3,26		2,67	
Min. Severity	Year	1983-1984		1997-1999		1997-1999		1982-1983		1982-1985		1982-1986		1996-1998		1996-1999		1999-2003	
	Value	21,13		24,91		35,39		22,94		49,62		49,69		27,64		35,47		45,28	
	Intensity	1,41		1,13		1,26		1,53		1,27		1,10		1,02		1,18		0,89	
Max. Intensity	Year	1981		1983-1985		1984-1985		1982-1983		1982-1985		1982-1986		1984		1996-1999		1996-1999	
	Value	2,2		1,51		1,49		1,53		1,27		1,1		1,08		1,18		1,23	

*: Number of total events per category; **Mean duration per category based on drought periods

APPENDIX D

a) *Drought characterization in Bebedero catchment based on SPI at different time scales*.

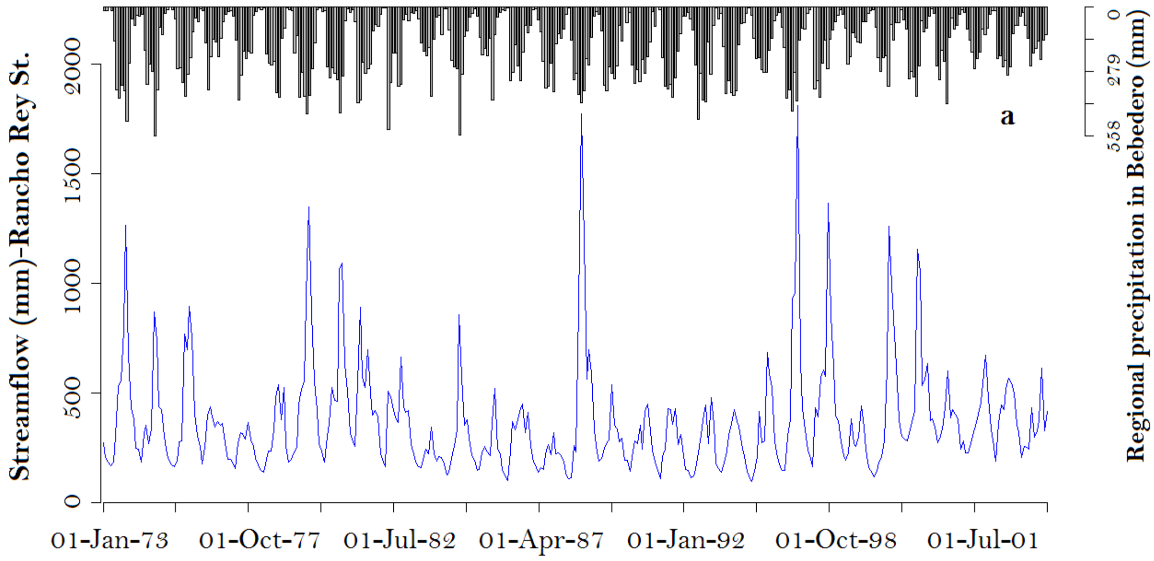
		Rio Blanco											
Stations		**Guayabo**						**La Fortuna**					
		Time Scale						**Time Scale**					
		3		6		12		3		6		12	
		*E**	*D***	*E*	*D*	*E*	*D*	*E*	*D*	*E*	*D*	*E*	*D*
Threshold	0 to -0.99	116	2,32	99	2,83	95	7,31	98	2,04	94	3,36	103	6,06
	-1.0 to -1.49	23	1,53	28	1,87	27	2,45	28	1,33	34	1,7	22	2,44
	-1.5 to -1.99	16	1,6	13	1,63	20	2,22	25	1,39	22	1,47	22	3,67
	-2.0 to less	16	2	16	3,2	16	4,00	15	1,67	14	2,8	19	9,50
Max. Duration	months	19		28		59		25		31		60	
Min. SPI	Year	1975		1975		1975		1986		1983		1983	
	Value	5,88		6,68		2,51		3,18		3,95		2,86	
Min. Severity	Year	1977-1979		1977-1979		1974-1979		1982-1984		1982-1984		1982-1987	
	Value	33,2		36,46		71,85		39		43,6		68,84	
	intensity	1,75		1,59		1,22		1,56		1,82		1,15	
Max. Intensity	Year	1974-1975		1974-1976		1974-1979		2000		1982-1984		1976-1979	
	Value	2,48		2,18		1,22		2,89		1,82		1,41	

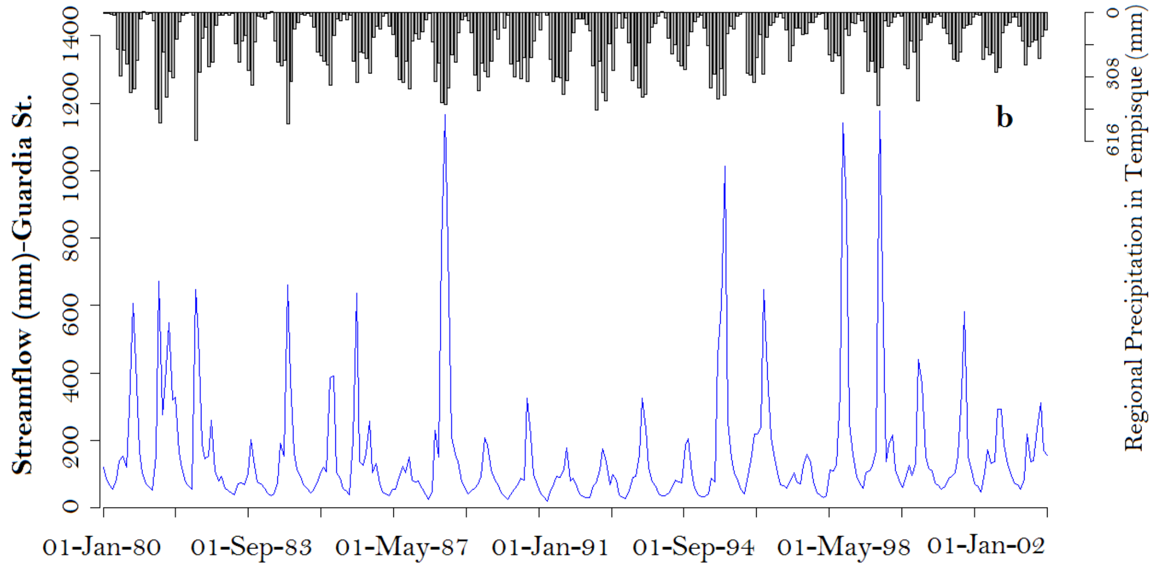
*: Number of total events per category; **Mean duration per category based on drought periods

		Río Tenorio																							
Stations		**Cuipilapa**						**Rio Naranjo Bagaces**						**Rio Naranjo**						**Montezuma**					
		Time Scale						**Time Scale**						**Time Scale**						**Time Scale**					
		3		6		12		3		6		12		3		6		12		3		6		12	
		*E**	*D***	*E*	*D*	*E*	*D*	*E*	*D*	*E*	*D*	*E*	*D*	*E*	*D*	*E*	*D*	*E*	*D*	*E*	*D*	*E*	*D*	*E*	*D*
Threshold	0 to -0.99	111	2,06	101	2,97	99	5,5	125	2,31	95	2,71	90	4,74	133	2,38	97	2,69	93	5,17	142	2,29	147	3,87	159	8,83
	/-1.0 to -1.49	27	1,35	39	1,77	35	2,5	26	1,63	37	1,85	36	3,27	22	1,69	42	2,1	40	3,64	27	1,35	26	1,63	21	2,33
	/-1.5 to -1.99	17	1,42	13	1,08	21	2,33	17	1,21	20	1,67	14	2	20	1,33	19	1,73	14	2,8	14	1,27	14	1,4	21	10,5
	/-2.0 to less	15	2,14	12	2	11	2,75	12	2	11	2,75	16	5,33	9	1,5	8	2,67	13	4,33	4	2	6	2	0	0
Max. Duration	months	12		29		42		29		39		87		29		44		87		11		20		55	
Min. SPI	Year	1986		1983		1983		1997		1997		1998		1997		1997		1998		1976		1977		1977	
	Value	3		2,78		2,19		2,82		2,77		2,82		2,86		2,55		2,59		2,38		2,54		1,92	
Min. Severity	Year	1984-1985		1985-1987		1997-1999		1996-1999		2000-2003		1996-2003		1996-1999		1996-2000		1996-2003		1977-1978		1976-1977		1975-1979	
	Value	13,73		30,91		36,34		32,75		47,27		108,37		32,12		45,93		105,6		11,68		16,03		57,56	
	intensity	1,14		1,07		1,3		1,13		1,21		1,25		1,11		1,04		1,21		1,17		1,46		1,05	
Max. Intensity	Year	1986		1982-1984		1983-1984		1973		1996-1999		1996-2003		1973		2000-2003		1996-2003		1973		1976-1977		1975-1979	
	Value	2,62		1,51		1,65		1,74		1,29		1,25		1,56		1,16		1,21		1,38		1,45		1,05	

*: Number of total events per category; **Mean duration per category based on drought periods

APPENDIX E


a
Streamflow (mm)-Rancho Rey St.
0
500
1000
1500
2000
Regional precipitation in Bebedero (mm)
0
279
558
01-Jan-73
01-Oct-77
01-Jul-82
01-Apr-87
01-Jan-92
01-Oct-98
01-Jul-01


b
Streamflow (mm)-Guardia St.
0
200
400
600
800
1000
1200
1400
Regional Precipitation in Tempisque (mm)
0
308
616
01-Jan-80
01-Sep-83
01-May-87
01-Jan-91
01-Sep-94
01-May-98
01-Jan-02

APPENDIX F

a) Enso years and Intensities

El Niño				La Niña		
Weak	Mod	Strong	Very Strong	Weak	Mod	Strong
1951-52	**1963-64**	**1957-58**	**1982-83**	**1950-51**	**1955-56**	**1973-74**
1952-53	**1986-87**	**1965-66**	**1997-98**	**1954-55**	**1970-71**	**1975-76**
1953-54	**1987-88**	**1972-73**	**2015-16**	**1964-65**	**1998-99**	**1988-89**
1958-59	**1991-92**			**1967-68**	**1999-00**	
1968-69	**2002-03**			**1971-72**	**2007-08**	
1969-70	**2009-10**			**1974-75**	**2010-11**	
1976-77				**1983-84**		
1977-78				**1984-85**		
1979-80				**1995-96**		
1994-95				**2000-01**		
2004-05				**2011-12**		
2006-07				**2016-17**		

Source: (Null, 2017)

APPENDIX G

a) *Flow duration curve for Tempisque and Bebedero catchment system*