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Introductory Essay

Variability of Climate and Water Resources in Central America

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Abstract

Disasters induced by natural phenomena have affected the society since the early days. Extreme hydro-meteorological events are perhaps one of the most common causes of nature-induced disasters. In Central America in particular, floods and droughts are associated to the climate variability of the region and are of major concern because of their large environmental and socio-economic impact. In order to reduce the negative consequences, it is important to understand these natural hazards. This report shows a literature review of previous studies of climate and water resources variability in the region. As well, reviews methods and tools that can be used for future studies on the subject. Since my PhD studies are within the framework of nature-induced disaster research, this review also includes as well some socioeconomic aspects of the Central American region, that help understanding why in many cases extreme hydro-meteorological events end up causing disasters. This review will hopefully set a good base for the development of my future research and for future possible collaborations.

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1 Introduction

1.1 Motivation

Disasters induced by natural phenomena have affected the society since the early days. It is suggested in some studies for example, that the Mayan civilization collapsed because of important drought events (Hodell, 1995; Haug et al., 2003). A similar situation is also thought to be responsible of putting an end to the Late Uruk society in southern Mesopotamia (Weiss and Bradley, 2001 taken from Staubwasser and Weiss, In Press). Recently, important events such as the tsunamis in Japan in 2011 and in South-East Asia in 2004 or the earthquake in Haiti in 2010 are examples that our societies continue (and will continue) to suffer the negative consequences of nature-induce disasters. Even though the situation is so, there are things we can do to ameliorate the negative consequences that the natural hazards can cause us.

There are regions more exposed than others to natural hazards, for example East and South Asia, Central America and western South America are regions threatened even by multiple hazards such as geophysical (e.g. earthquake, volcano) and hydro-meteorological (e.g. drought, flood) driven-hazards. (Dilley et al., 2005). Central America in particular, is one of the most exposed regions to natural hazards (CEPAL, 2000). Features like tropical storms, easterly waves, the Mid -Summer Drought, cold fronts, among others, are part of the common climatic features of this region and what makes it worth of study in the context of an integrated research. Floods and droughts are of major concern because of their environmental and socio-economic impact such as in public health, infrastructure and economic activities like agriculture and hydropower generation, fishery, tourism, among other impacts.

About two thirds of the population in Central America live in urban areas nowadays, the urban growth has been rapid and unfortunately, unplanned. This has generated a big pressure on resources (e.g. water) and services and sets a scenario with different economic and social problems (Programa Estado de la Nación, 2011). As a consequence, the vulnerability to natural hazards has increased in the region because of this rapid and unplanned urban, industrial and demographic growth. It has also increased because of the associated environmental deterioration (due to the mismanagement of natural resources) and the poverty in both, rural and urban areas (BID, 2005; Mora, 1999; Mora and Keipi, 2006). Besides all of this, even though some progress has been done in the past few years, the governments prioritize mitigation, emergency and efforts in disaster response rather than in the reduction of vulnerability (Mora, 2009).

1.2 Research plan

The main objective I want to fulfil during my PhD studies is to contribute with the understanding of variability of climate and water resources in Central America. Extreme hydro-meteorological events take place regularly in this region and they are associated to the climate variability, causing significant socio-economic and environmental impacts. I plan to focus on the study of floods and droughts and their connection with the climate variability of the region. Studies like this are very important since even though extreme hydro-meteorological events have so large negative impacts in the region, studies about them remain scarce.

During my studies I plan to make use of hydrological models. Hydrological models are simplified representations of the water cycle, this means that these can represent for example, for a certain amount of rainfall, what part of the rainfall stays on the leaves, what part goes deep down into the soil and which stays on the surface in form of runoff. Such a model is a valuable tool in climate variability studies, it could be used for example, to generate historical streamflow data for the region, since such type of data are very scarce. The simulated historical data could eventually be used to study past drought and flood events. Valuable information like e.g. correlation between hydrological droughts (reduced streamflow or of groundwater levels) or floods and some oceanic and/or atmospheric feature like El Niño Southern Oscillation (ENSO) could be obtained from these data. Hydrological models can also be used for forecasting purposes, so droughts and floods could be predicted with these models.

One of the largest limitations of making climate variability studies in the region though, is the difficulty of having access to a good observational network of meteorological and hydrological data. Models for example, are very affected by the quality of the data used as input, so errors on these data could add significant amount of uncertainty in the results. Therefore, a secondary objective I want to achieve during my studies is to tackle the problematic of hydro-meteorological data availability in the Central American region. A way to tackle the problematic (at least that of meteorological data) is to draw upon coarse-resolution-scale General Circulation Models (GCMs). These options though, have a limitation: they fail at representing some characteristics of the climate on regional scales due in part, to problems with the spatial resolution of the model. A way to address this limitation is by applying downscaling techniques, that is, to reduce the scale of the data. There are two types of downscaling techniques I could make use of, those are: statistical and dynamical techniques. This actually gives opportunity for collaboration within CNDS with the student Tito Maldonado. Tito will soon start his PhD in meteorology and his field of study is related to dynamical downscaling in Central America. I could collaborate with him in dynamically-downscaling coarse resolution meteorological data, this would be of great importance since these data could be used as input in hydrological models (this process is known as coupling) to make the intended studies.

This essay is organized as follows: general information about nature-induced disasters with a focus on droughts and floods and review of past studies in the Central American region can be found in section 2. In the case of droughts, a description of five indices used in an ongoing study is given. A background on the region of study: Central America is given in section 3. This section starts with a description of the socio-economic aspects that make the region more vulnerable to the negative consequences of the natural hazards. Section 3 includes as well a description of the climate of the region. In section 4 a description and background information of hydrological models is given. In that same section is also found a brief review of climate models (due to the possibility of coupling this with a hydrological model) as well as a description of downscaling techniques that can be used, and a brief review of previous studies that attempt to couple a hydrological and an atmospheric model. Current and future work/courses and description of time plan is given in section 5.

2 Nature-Induced Disasters

2.1 Definition and generalities

Source	**Disaster Definition**
EM-DAT*	An unforeseen and often sudden event that causes great damage, destruction and human suffering. Though often caused by nature, disasters can have human origins. Wars and civil disturbances that destroy homelands and displace people are included among the causes of disasters. Other causes can be: building collapse, blizzard, drought, epidemic, earthquake, explosion, fire, flood hazardous material or transportation incident (such as a chemical spill), hurricane, nuclear incident, tornado, or volcano
UNISDR**	A serious disruption of the functioning of a community or a society involving widespread human, material, economic or environmental losses and impacts, which exceeds the ability of the affected community or society to cope using its own resources
	Vulnerability Definition
EM-DAT	Degree of loss (from 0% to 100%) resulting from a potential damaging phenomenon
UNISDR	The characteristics and circumstances of a community, system or asset that make it susceptible to the damaging effects of a hazard.
	Risk Definition
EM-DAT	Expected losses (of lives, persons injured, property damaged and economic activity disrupted) due to a particular hazard for a given area and reference period. Based on mathematical calculations, risk is the product of hazard and vulnerability
UNISDR	The combination of the probability of an event and its negative consequences.

* The Emergency Events Database (EM-DAT)

**The United Nations International Strategy for Disaster Reduction

Table 1: Table Some Relevant Definitions

Since my PhD studies are within the framework of a nature-induced related project, the most reasonable is to start with some generalities about them. There are different definitions (see table 1) that can be found in the literature for the concepts disaster, vulnerability and risk. The definition of nature-induced disasters always includes two components: the natural hazard (like earthquakes, volcanic eruptions, landslides, floods, and droughts) and its effect in the society. There cannot be a nature induced disaster if the society is not under the threat of a natural hazard, so as there cannot be one if there is no society under the impact of a natural hazard. *Natural disasters* is a commonly used term, but it is debated in the literature on whether it should actually be used or not. The ones that oppose its use claim that disasters are man-made and that they are the consequence of bad decisions taken by the society (Mora, 2010; Neumayer and Plümper, 2008). A hint of the fact that disasters are not natural, Neumayer and Plümper (2008) say, is given by the fact that such disasters do not affect people equally when they strike, but their impact depend on the vulnerability of the affected.

As said above, nature-induced disasters do not strike with the same strength in all the places. According to a document from CEPAL and IDB (2000), developing countries suffer in general the largest social, economic, environmental, and political negative consequences of nature-induced disasters. An example given in the same document, comes from the year 1998, in which 95% of the deaths due to nature-induced disasters were from developing countries. There are other aspects as well that can determine the magnitude of the impact of disasters, such aspects can be gender, ethnicity and economic class. Several studies for example, conclude that nature-induced disasters affect women differently than man, with women suffering in many of the cases, the heavier burden (UN, 2010; Neumayer and Plümpen, 2008). Another example is given by CRS (2005) which concluded that during the disaster caused by hurricane Katrina in New Orleans (USA) in August 2005, the impacts were harder on the poor and on the African Americans.

Vulnerability is greatly associated to the social processes developing in disaster-prone areas, so it depends in large part on the political decisions taken before and after the disaster (IDB/CEPAL, 2008). The problems behind the un-development are the same than those that contribute to the vulnerability, therefore this close link (IDB, 1999). This problem seems to be harder to solve because development is frequently obstructed by the impact of natural disasters (Mora, 2010; CEPAL/IDB, 2000). This turns then into a cycle from which is difficult to step out: undeveloped countries are more vulnerable to disasters and disasters themselves hinder development.

An approach to reduced vulnerabilities to nature-induced disasters is *Disaster risk management*. Mora (2009) defines disaster risk management as “a policy promoting the identification, analysis and quantification of the probability of damage that a natural hazard might cause, considering the vulnerability of the human environment and the ways to prevent and mitigate the losses in advance”. Risk management is commonly divided into two phases: the pre-disaster which includes risk identification, risk mitigation, risk transfer, and preparedness and post-disaster period which includes emergency response and rehabilitation and reconstruction (Freeman et al., 2003). The pre-disaster phase is very important and in Latin America and the Caribbean for example, a region highly exposed to potentially destructive natural hazards, a lot of the effort in the past has been placed into the post-phase rather than in disaster prevention (pre-phase). This lack of preparedness, as it is to expect, has brought negative consequences. Now at least more attention is given to vulnerability reduction (although Mora,2009 thinks is still not enough) and literature on disaster prevention and preparedness for the region can be easily found (e.g. CEPREDENAC-SICA, 2010; IADB, 2007).

As McEntire (2007) says, disaster risk management is complex and needs a multi and interdisciplinary approach. Such approach can help to have a better understanding and an efficient formulation and implementation of policies. We know for example, that if a given disaster takes place, there are responses from national and maybe even international emergency agencies and some other groups from the public and private sector. McEntire points out how the collaboration and communication of all the latter are important for a successfully attention of the emergency, and that it is also very important to continue with the preparation and collaboration for a next event. It is of course, more efficient to know before hand the responsibilities of each organization and how these can contribute among them, than if the duties are overlapped and there are gaps left without solution on the time of the event. Collaboration and a good communication among the different disciplines, groups and institutions taking part in the preparedness and response process is very important. However there should be special care since the different disciplines might not speak exactly the same "language", meaning that a term or concept for political science might not be the same for natural science (McEntire, 2007). Communication can also be hard to implement among different organizations or groups if there are no previous channels or routines of communication, and/or if there is lack of trust among them and/or if the level of importance of what should be known and informed varies (Boin and t'Hart, 2010)

A very useful tool for almost all of those that are involved with nature-induced disasters studies are the disasters databases. There are several of these, perhaps the best well know due to its international character is the Emergency Disaster Database (EM-DAT) developed and maintained by the Centre for Research on the Epidemiology of Disaster (CRED), Department of Public Health, Université Catholique of Louvain (Brussels, Belgium).

The criteria that EM-DAT uses for listing an event in history as a disaster is that it fits at least one of the following criteria:

- 10 or more people killed
- 100 or more people affected
- declaration of a state of emergency
- Call for international assistance

Another database with more regional character is available at the Disaster Inventory System - DesINventar (Sistema de Inventario de Desastres). Developed by different groups of researchers, academicians and institutional actors linked to the Network of Social Studies in the Prevention of Disaster in Latin America (LA RED, in spanish). Special care is recommended when using such databases on the definitions used of each natural hazard. Results of information do not coincide and this is probably due to differences in definitions and sources.

The prevention and mitigation of nature-induced disaster requires a lot of work and coordination. As Waring et al. (2005) said "Disaster response is a complex process that requires continual review and revision of preparedness missions at the local, national, and international level ". The process of reducing the negative consequences of the impact of natural hazards is a duty that should involve several different organizations and disciplines and most important of all, it should be a continues task.

2.2 Droughts

2.2.1 Drought definition and generalities

Droughts affect almost all the climatic zones of the world, independent on whether these are dry or humid areas (Mishra and Singh, 2010). According to Dilley et al. (2005) areas susceptible to droughts are: some parts of the midwestern United States, Central America, northeastern Brazil, the sub-Saharan belt, the Horn of Africa, southern and central Africa, Madagascar, southern Spain and Portugal, central Asia, northwestern India, northeast China, Southeast Asia, Indonesia, and southern Australia. Droughts have significant impacts all around the world, they cause substantial economic losses to the farming community of about billions of dollars (Narasimhan and Srinivasan,2005). However, such economic impacts are not easy to study since these are commonly undervalued because of the lack of a visible damage outside agriculture and the large quantity of indirect losses compared to direct losses (Below et al., 2007).

These type of hazards are difficult to study, they develop slowly and their spatial and temporal extent are hard to determine (Kim et al., 2009; Morid et al., 2006; Serrano et al, 2010; WMO, 2006). Besides this, the impacts of droughts vary from region to region, all of these makes it hard to have a universal definition of drought. For this reason, several definitions can be found depending on the sector it affects, whether it is the economic or social sector (Wilhite and Glantz, 1985). Also, different definitions according to disciplines are found in the literature, these being: meteorological, agricultural, hydrological and socio-economical drought (Wilhite and Glantz, 1985; Mishra and Singh, 2010). Mishra and Singh (2010) make a review of these concepts and summarize that a meteorological drought is defined as a lack of precipitation over a region for some period of time. An agricultural drought refers to a reduction in soil moisture that consequently can affect the crops. Hydrological drought is related to a period with insufficient surface and subsurface water resources. Socio-economic drought is associated to demand and supply of some economic good, more specifically, when demand exceeds supply. Socio-economic droughts can be associated to hydrological, agricultural and meteorological drought.

Droughts can cause several impacts on different important economic activities. Impact on agriculture for example, can have negative consequences in the society such as undernourishment and economic problems to the families that depend on farming, which can later transform into social problems like lost of home, school drop-out and child labour (Brenes, 2010). Such a situation occurred in Guatemala in 2009, where a drought caused an alimentary crisis that affected around 34000 poor families and was the cause of undernourishment and many deaths (PESA-FAO, 2009). Hydropower generation is another economic activity that can be affected under a drought episode; if the levels on the hydro-power dams seem reduced, it can result in blackouts and energy rationing (Brenes, 2010). Droughts may also have an impact on other sectors such as tourism and recreation, public utilities (e.g. water drinkable water and sanitation), horticulture and landscaping services, navigation and industries (Ding et al., 2010). The environment can as well suffer many negative consequences since droughts can lead to fires, damage of air and water quality, lead to soil erosion and damage of wildlife habitat (Monacelli, 2005).

2.2.2 Comparison of five meteorological drought indices

In order to be prepared and be able to reduce the impacts of droughts, several drought indices have been developed. These indices can give information such as intensity, duration, severity and spatial extent (Mishra and Singh, 2010). Drought indices somehow facilitate the study of droughts, by being a mean of quantifying their characteristics.

Drought indices can be used in future drought-related studies in Central America, a region where drought-related studies still remain scarce. In my current work (see section 5) we aim at evaluating the capability of the indices described below, to characterise the temporal and spatial extent of past drought events. The resulting best performing index (indices) could be used in future studies to find the connection of the drought events to the regional climatic variability. The index (indices) could also be used to provide early drought warning system allowing planning in areas like water management and agriculture.

- **Percent of Normal Precipitation (PNP)**: a simple approach calculates the depart from normal of precipitation for a certain period and used and reviewed by studies such as Yang and Wu (2010) and Morid et al. (2005). Calculated as:

$$P_a = \frac{P - \bar{P}}{\bar{P}} \times 100\% \tag{1}$$

$$\bar{P} = \frac{1}{n} \sum_{i=1}^{n} P_i \tag{2}$$

  Where P_a is PAP, P is the rainfall for a certain period, $\bar{P}$ is the long-term average for that period. Advantages of this index are its simplicity of calculation, its possibility to be used at different time scales. Its limitations are that the index relies on the assumption that the precipitation is normally distributed (which in most of the cases is not). Also that, even though it is widely used, its application is strongly limited by its inherent nature of dependence on the mean, so that two different areas with different amounts of mean rainfall can have the same deviations from the long-term mean and this should be interpreted with care (Naresh Kumar et al., 2009).

- **Standardized Precipitation Index (SPI)**: This precipitation based index developed by McKee et al. (1993) can be calculated for a variety of time scales (1 - 3 -6 - 9 - 12 - and 48-month periods), considering shorter-term problems such as soil moisture and longer-term problems such as in groundwater supplies, streamflow and lake reservoir levels (McKee, 1993; Hayes et al., 1999). The SPI is calculated by fitting the precipitation record to a probability distribution (gamma and Pearson Type II are commonly used). Then, the cumulative distribution is transformed to a normal distribution with mean zero and standard deviation of one. SPI values below zero indicate drought conditions (see table 2). The main strength of the index is its versatility in time since it can be calculated for multiple scales (Mishra and Singh, 2010) and the fact that it is widely used around the world. On the other hand the length of the data record and the probability distribution to which the record is fitted affect the SPI values, so this should be handled with care (Mishra and Singh, 2010).

- **Deciles of precipitation (DI)**: This index, developed by Gibbs and Maher (1967) is also simple to calculate, based only on precipitation and is non-parametric. The long-term data (unit of time chosen, monthly, yearly, etc.) are arranged from lowest to highest and separated into 10 groups or deciles, each containing a tenth of the data. If the data falls into the first decile for example, is considered to be extreme drought (see table 2 for intensities). The index is simple, but requires a long record of data for accuracy in its calculation (Tsakiris et al., 2004).

- **Effective Drought Index**: Byun and Wilhite (1999) developed this daily-calculated drought index as a measure to overcome the limitation associated with other indices. Most of the drought indices use monthly or even longer periods and this can mean that some information is being missed considering that the water amount of a region affected by a drought could go back to normal conditions with only a one-day rainfall (Byun and Wilhite, 1999). The index considers the fact that accumulation of daily water has different weights with the passage of time, so a heavy rain 1 day ago does not weight the same on the index as if it happened 40 days ago (Kim et al., 2009). The index is calculated using the equation:

  $$EP_i = \sum_{n=1}^{i} \left[\left(\sum_{m=1}^{n} P_m \right) / n \right] \tag{3}$$

  where
  i = duration of summation (DS), is the period over precipitation is summed, commonly 365
  P_m = precipitation of m days before

  After having the EP, the 30-year mean of EP, the MEP, should be calculated for each calendar day. After this step the deviation from the mean (DEP) can be calculated:

$$\text{DEP} = \text{ EP} - \text{ MEP} \tag{4}$$

$$\text{EDI} = \text{ DEP/SD(DEP)} \tag{5}$$

A limitation with the index is that daily-precipitation data are more difficult to obtain than monthly data.

- **Standardized Precipitation Evapotranspiration Index (SPEI)**: Developed by Seerano et al. (2009), this index is calculated in a similar fashion than SPI, just that instead of fitting the precipitation distribution, one must fit the accumulated surplus/deficit of the climatic water balance. Precipitation and temperature are needed to estimate the evapotranspiration values. Evapotranspiration can be calculated with different approaches, for example Serrano et al. (2009) uses Thornthwaite formula calculated as:

$$PET = 16K\left(\frac{10T}{I}\right)^m \tag{6}$$

where T is the monthly-mean temperature in °C I is the heat index, calculated as the sum of 12 monthly index values i, which in hand is calculated with

$$i = \left(\frac{T}{5}\right)^{1.514} \tag{7}$$

where m is a coefficient that depends on $I : m = 6.75 \times 10^{-7}I^3 - 7.71 \times 10^{-5}I^2 + 1.79 \times 10^{-2}I + 0.492$ and K is a correction coefficient calculated as

$$K = \left(\frac{N}{12}\right)\left(\frac{NDM}{30}\right) \tag{8}$$

NDM is the number of days of the month and N is the maximum number of sun hours, which is calculated with

$$N = \left(\frac{24}{\pi}\right)\bar{\omega}_s \tag{9}$$

here $\bar{\omega}_s$ is the hourly angle of sun rising, which is calculated using

$$\bar{\omega}_s = arccos(-tan\phi tan\delta) \tag{10}$$

$$\delta = 0.4093\text{sen}\left(\frac{2\pi \text{J}}{365} - 1.405\right) \tag{11}$$

where J is the average Julian day of the month.

Category	**PNP (%)**	**EDI**	**SPI**	**DI**
Extremely wet		$\geq$ 2.5	$\geq$ 2.00	$\geq$90
Very wet		1.50 to 2.49	1.50 to 1.99	80 to 90
Moderately wet	$\geq$ 110	0.7 to 1.49	1.00 to 1.49	70 to 80
Near normal	80 to 110	-0.69 to 0.69	-0.99 to 0.99	30 to 70
Moderately dry	55 to 80	-0.7 to -1.49	-1.00 to -1.49	20 to 30
Severely dry	40 to 55	-1.5 to -2.49	-1.50 to -1.99	10 to 20
Extremely dry	$\leq$ 40	$\leq$ -2.00		$\leq$ 10

Table 2: Comparison table for the categories of the different indices

Morid et al. (2006) categorized the different values for the different drought indices (see table 2), this makes it easier for comparison purposes.

Drought studies that characterize the extent of droughts and their connection to the regional climatic variability remain scarce in Central America. Mendez and Magaña (2010) studied the driver mechanisms of prolonged droughts (more than one year) over Mexico and Central America. In this study a seesaw pattern in the precipitation anomalies between the northern part of Mexico and Mesoamerica (south part of Mexico and Central America) was recognized: frequently when there is drought in northern Mexico, anomalously wet conditions are experienced in Mesoamerica and vice versa. Besides in the same study the relationship between the strength of the Caribbean Low-Level Jet (CLLJ) and precipitation anomalies in the region was recognized, showing that a stronger-than-normal CLLJ inhibits activity of easterly waves, this meaning less precipitation for Mesoamerica. Other authors have studied the relationship between the start or end date of the rainy season or Mid-Summer Drought over Cenrtal America and the interannual variability of the sea surface temperature (SST) in the tropical north Atlantic and the eastern tropical Pacific (Alfaro et al., 1998; Enfield and Alfaro, 1999; Alfaro, 2002). These studies agree that at an interannual scale, dry (wet) years are related with colder (warmer) SST anomalies in the Tropical Atlantic than in the Eastern Tropical Pacific, meanwhile at an interdecadal scale, precipitation shows positive correlations with the anomalies of both oceanic regions. Relations with El Niño Southern Oscillation (ENSO) and precipitation and its driver mechanisms have been done (Ropelewski and Halpert 1987; Waylen et al. 1996; George et al. 1998; Mora 2000). These studies found a relationship between El Niño phase and negative anomalies of annual precipitation in Central America and excess of rain during La Niña.

2.3 Floods

The International Glossary of Hydrology (WMO-UNESCO, 1992) defines **flood** as:

1. *Rise, usually brief, in the water level in a stream to a peak from which the water level recedes at a slower rate*
2. *Relatively high flow as measured by stage height or discharge.*
3. *Rising tide*

Every year we hear or read in the news about large flood events all around the world, causing substantial damages and causing deaths. According to Dilley et al. (2005) flooding occurs in more than one-third of the land area of the world, where resides around 82% of the whole world population. The authors name the regions more susceptible to floods, these being: large areas of the midwestern United States, Central America, coastal South America, Europe, eastern Africa, northeast India and Bangladesh, the Korean peninsula, Southeast Asia, Indonesia, and the Philippines.

According to Ward and Robinson (2000) among the most common causes of river floods are the direct or indirect effect of climatological events, such as an excessive amount of rain and/or excessively long rainfall. In the case of high latitudes areas, flooding can also be caused by snow-melt. The authors also point out how human activity can intensify the situation in a flood event, like urbanization for example, which implies most of the times covering the areas with less permeable surfaces, causing changes in the hydrological response of the catchment.

In Central America, flooding are the result of the variability of climate. Storms, hurricanes, the Intertropical Convergence Zone (ITCZ), easterly waves, cold fronts that reaching the region are some of the features that may cause flood events. According to Waylen and Laporte (1999), the processes behind flood generation in this region are only driven by rainfall. The study made by the authors investigate flood characteristics in Costa Rica for four rivers in the Pacific watershed focusing in associations of the generation processes with El-Niño Southern Oscillation (ENSO). According to the study, in general the flood characteristics of the countries (and their regions) at the western part of Central America are more prone to interannual variability. This, the authors explain, is due to the proximity they have with large scale climatic variability associated with ENSO. They found that in the Pacific side of Costa Rica during an El Niño event, the flood frequency is reduced due to the induced ENSO signals over the region: a longer Mid-Summer drought or veranillo, the reduced frequency of tropical storms and the reduced frequency of the cold fronts coming from the north.

The reasons why floods are so frequent in the Central American region are not only related to the natural hazards. According to the BID (1999) in Central America, the highest density of people are living in the cities and a large percentage of those people are living in poverty as well. This means that there has been a rapid and unplanned urban growth, resulting in people grouping in non-formal settlements sometimes with no drainage at all, located in flood plains or steep slopes. The same study points out other anthropogenic causes that has worsen the situation in the region such as deforestation, overgrazing, alteration of the river channels and some agriculture practices. All of this sets a perfect scenario for the easy development of floods and are part of the things that should be changed in order to reduce vulnerability.

It is important to point out that even though droughts and floods are both hydro-meteorological extremes, they are very different. Droughts develop slowly and sometimes their effects are not even noticed. Floods on the other hand, occur fast (in the order of hours or days) and the impacts are visible when they take place. Destruction of infrastructure, landslides, interruption of services are some of the visible impacts that flood have.

3 Region of study

3.1 Climate of Central America

Central America is located near the equator. Is a narrow piece of land limiting with the Caribbean Sea to the east and with the Pacific Ocean to the west. A mountain range crosses the isthmus and has a big influence in the climate when interacting with the predominant flow. This influence is so large that separates the precipitation regimes into two different ones, one to Pacific side and the other to the Caribbean side. The position of Central America exposes it to be under the influence of different phenomena with seasonal, interannual and even interdecadal scales (Alfaro, 2002). El Niño Southern Oscillation, hurricanes, the ITCZ are few examples of these features.

In general terms, the temperature shows small variations at an annual scale (Portig, 1965), precipitation on the other hand, shows high variability (Alfaro, 2002). The annual cycle of precipitation for the Pacific slope of the region shows a bimodal distribution with two maxima, one in June and September/October. The dry season on the Pacific side is well defined and goes from December to April. During these months the trade winds velocity increases over the region due to the southward shift of the North Atlantic semi-permanent high pressure system (Hastenrath, 1966). This strengthening of the winds and their interaction with the mountain range leads the Pacific side "dry" due to the rain shadow effect and the Caribbean (windward side) with heavy precipitations. During this period, between the months of December-March, Central America suffers the intrusion of cold air masses coming from the north commonly known as the "nortes" (Rivera and Amador, 2008). A similar rain-shadow effect mechanism produced by this feature produces precipitation over the Caribbean side of the isthmus and drier condition on the Pacific (Rivera and Amador, 2008). A relative minimum of precipitation occurs during July/August, this period is commonly called the Canícula, Veranillo or Mid-Summer Drought (MSD, Magaña et al.,1999). Un like the Pacific, the Caribbean slope does not present a defined dry season (Alfaro and Cid, 1998).

Rainy season in the Pacific side occurs during the months of May to November. During these months the high pressure system from the North Atlantic shifts to the north and as a consequence, the trades reduce their intensity. The Intertropical Convergence Zone (ITCZ) shifts its position, according to Waylen and Laporte (1999), from about 3°N in February to about 10°N in June/September, bringing a belt of unstable air and heavy storms. Precipitation during this period is also caused by tropical storms and cyclones most commonly over the Atlantic, the authors say. These storms can cause a direct (for the Caribbean side) and indirect effect caused by the enhanced westerlies and trades disruption, once the storm enters the Caribbean.

Amador (1998) describes a feature that develops in the central part of the Caribbean Sea from May to July called the Intra-Americas or Caribbean Low-Level Jet (IALLJ or CLLJ, respectively). Is during these months where the wind speed reaches its maximum. The CLLJ can influence the development of tropical convective systems (Rivera and Amador, 2008 in Amador et al., 2000) and could interact (and intensify) with other features like the easterly waves (Amador, 1998)

At an interannual and interdecadal scale, the climate of Central America has been found to have strong association with the east equatorial Pacific and the tropical north Atlantic (TNA) through teleconnection mechanisms (Alfaro, 2002). Such is the case of ENSO, one of the phenomena that through its teleconnections explain much of the climate variability of the world (Díaz and McGraaf, 2000). The signal over Central America is quite characteristic because of the influences ENSO has over the atmospheric flows and the interaction of these flows with the topography of the region (Waylen et al., 1996). During an el Niño event the strength and period of the summer trade winds increase over the Caribbean (Waylen and Laporte, 1999.). Studies have found and continue finding a relationship between the frequency of tropical storm activity in the Atlantic Ocean and the different phases of ENSO. Some of them have found that the number of tropical storms over the Atlantic is reduced during an El Niõ event. (Gray, 1984; Vitart and Anderson, 2001), which according to Alfaro and Amador is related to the strong westerly winds (which occur over the Caribbean and Atlantic during a Niño event) that blow in the high troposphere (200 hPa). The reduction of tropical storms over the Atlantic during an El Niño event means a reduction of the accumulated precipitation on the Caribbean side due to the direct effect or on the Pacific side due to indirect effects.

3.2 The hydro-meteorological data-availability problem

Hydro-climatic variability and forecasting studies are directly affected by the quality of meteorological, land-surface and hydrological observations. Hydrological models, for example, are particularly sensitive to meteorological and land-surface input data as well as to the hydrological data used for calibration. Errors in either type of data could interact with the structural errors of the models in a complex manner. However, a reasonably good database of meteorological, hydrological and land-surface data covering a relatively short period of time, could serve to calibrate a hydrological model.

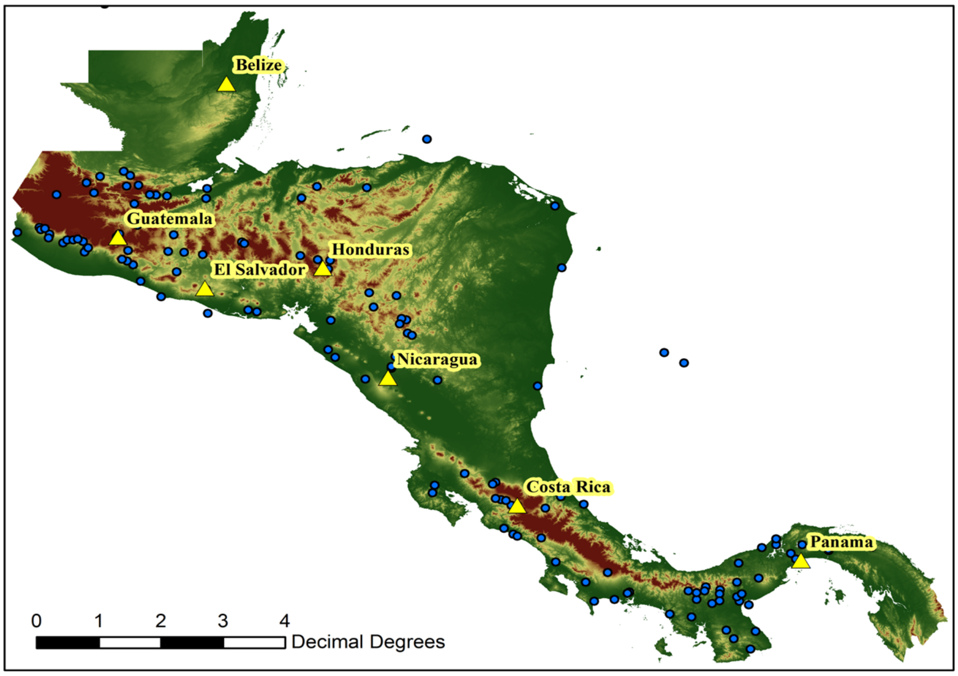

Figure 1: The Central-American region, capitals and locations of the meteorological stations in the CIGEFI-UGR database (1958-2009)

Unfortunately, access to good observational network of meteorological and hydrological data represents a problem in Central America, several authors address this problematic (e.g. Portig, 1965; Aguilar et al., 2005; Westerberg et al., 2011).The data availability problem, in the case of daily precipitation, can be illustrated by the dataset of the Centro de Investigaciones Geofísicas (Center for Geophysical Research) of the Universidad de Costa Rica (UCR), in what is referred to as the CIGEFI/UCR station network. The spatial density and the changes in temporal coverage shown in figure 1 and figure 2 reveal two alarming issues. In the first place, the low network density could not efficiently describe the spatial heterogeneity of climate of the region, even under the assumption that all stations have no significant missing data. There are certainly no stations covering large regions and it has to be determined if the stations available could be considered representative of the region under study, given the large spatial climatic variability. Secondly, around 1971, as a result of the declaration of the International Hydrological Decade, a significant improvement of the station network followed.

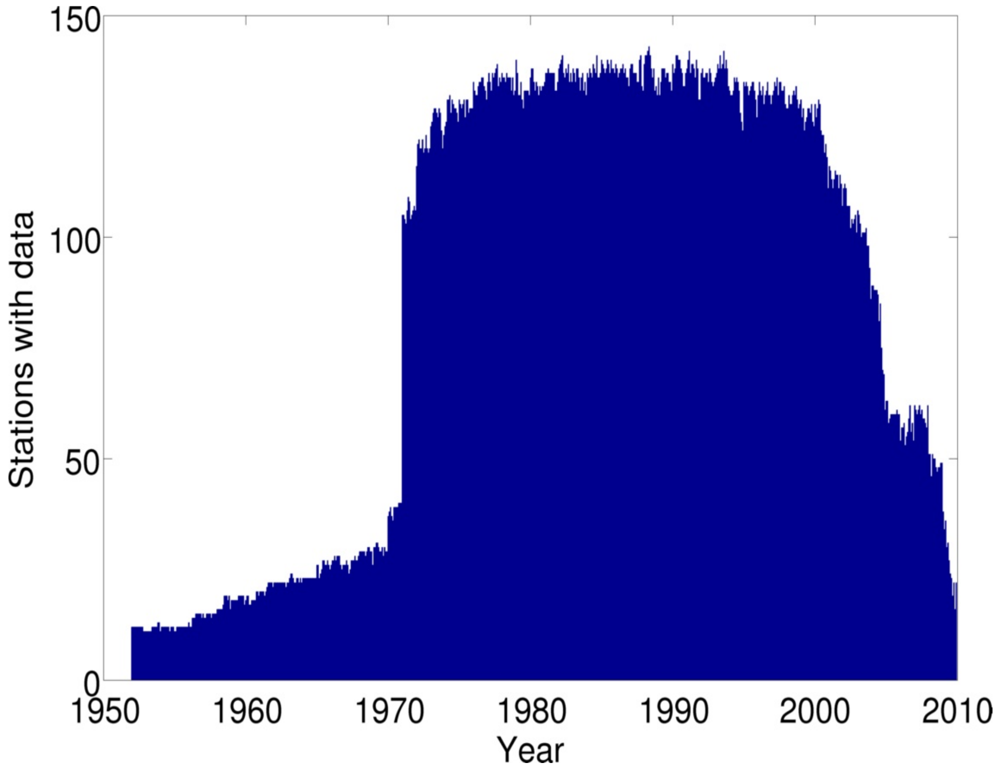

Figure 2: Graph showing the number of reporting stations with monthly precipitation data in Central America, having less than 15% missing data in any particular month, CIGEFI/UCR data base from 1973-2003.

Unfortunately, the network has been experiencing a steady decline since 2000, in a period when climate change awareness has dramatically increased in other parts of the world. It should be mentioned that the decline in data shown in this graph comes two main reasons: 1) A number of stations of the network have been out of service and 2) Obtaining reports from some of these stations has been increasingly difficult.

There are different hydro-meteorological databases currently available. Table 3 contains the different available datasets until now available for the studies I plan to do in variability of climate and water resources. Howerver, there are some limitations with each of the datasets. The spatial resolution of CRN073 ERA-INTERIM and CRU might be still too coarse for the required from some studies. The skill of TRMM at the daily scale does not seem to be as good when reproducing the climate variability of the region as in the monthly skill and it could also be too short for climate studies. CIGEFI-UCR, as commented before is not conformed of a dense network and areas in the Caribbean has no information at all or there are many time gaps in the data from the rest of the stations. CRU even though it says is available from 1909, it is until the 1950s there are data (earlier than that is just missing data or NANs). Pedreros has a good resolution, but unfortunately is available until 2004.

Figure 3 shows the cumulative frequency distributions of the different available precipitation datasets for the seven Central America capitals. Comparing to the station data through visual examination one can see the different datasets perform differently with the different points of

Data base	Type	Space Res.	Time Res.	Period Avail.
CRN073	Precipitation Combined satellite and station data	0.5° x 0.5°	daily	1958 to 2000
TRMM	Precipitation Combined satellite and station data	0.25° x 0.25°	3-hourly/daily/monthly	1998 to the present
ERA-Interim	Precipitation reanalysis	0.5° x 0.5°	monthly	1979 to the present
		0.25?		
CIGEFI-UCR	Precipitation Temperature station		daily	1952 to 2009
Pedreros	Precipitation station, satellite	0.05° x 0.05°	monthly	1970 to 2004
CRU	Precipitation	0.5° x 0.5°	monthly	1909 to 2009

Table 3: Available Data bases for Central America

study. San Salvador and Managua seem to have closer curves from all the different datasets compared to the station data. The case of Panama City is very interesting, since it seems to have the worst fit from the different datasets with respect to station data. One of the possible explanations could be related to the wideness of the country. Panama is a very narrow country and like in the rest of Central America, it has two different precipitation regimes, one on the Caribbean side and the other on the Pacific side. The country is so narrow that depending on where the grid cell is centred (especially for those datasets with coarser spatial resolution), the value could actually correspond to either of the two regimes or to a mixed signal between the two due to extrapolation.

A good example of the problems with the hydrological monitoring network in Central America is given by Westerberg (2011). The author comments that during hurricane Mitch in October 1998, this network was destroyed during the floods produced by the hurricane and after that, the data availability and quality have been reduced.

The problematic of hydro-meteorological data availability sets a good example of a possible future collaboration within other disciplines. Perhaps some social scientists could help in finding the answer to: why are less measurements of hydro-meteorological data being done now than some decades ago? How should we natural scientists communicate to politicians about the importance of having such observation networks?

3.3 Brief description of Central America socio-economic background

According to CEPAL (2000), Central America is one of the regions that is most exposed to natural hazards. It lays in at least four tectonic plates and it is located in a region with high

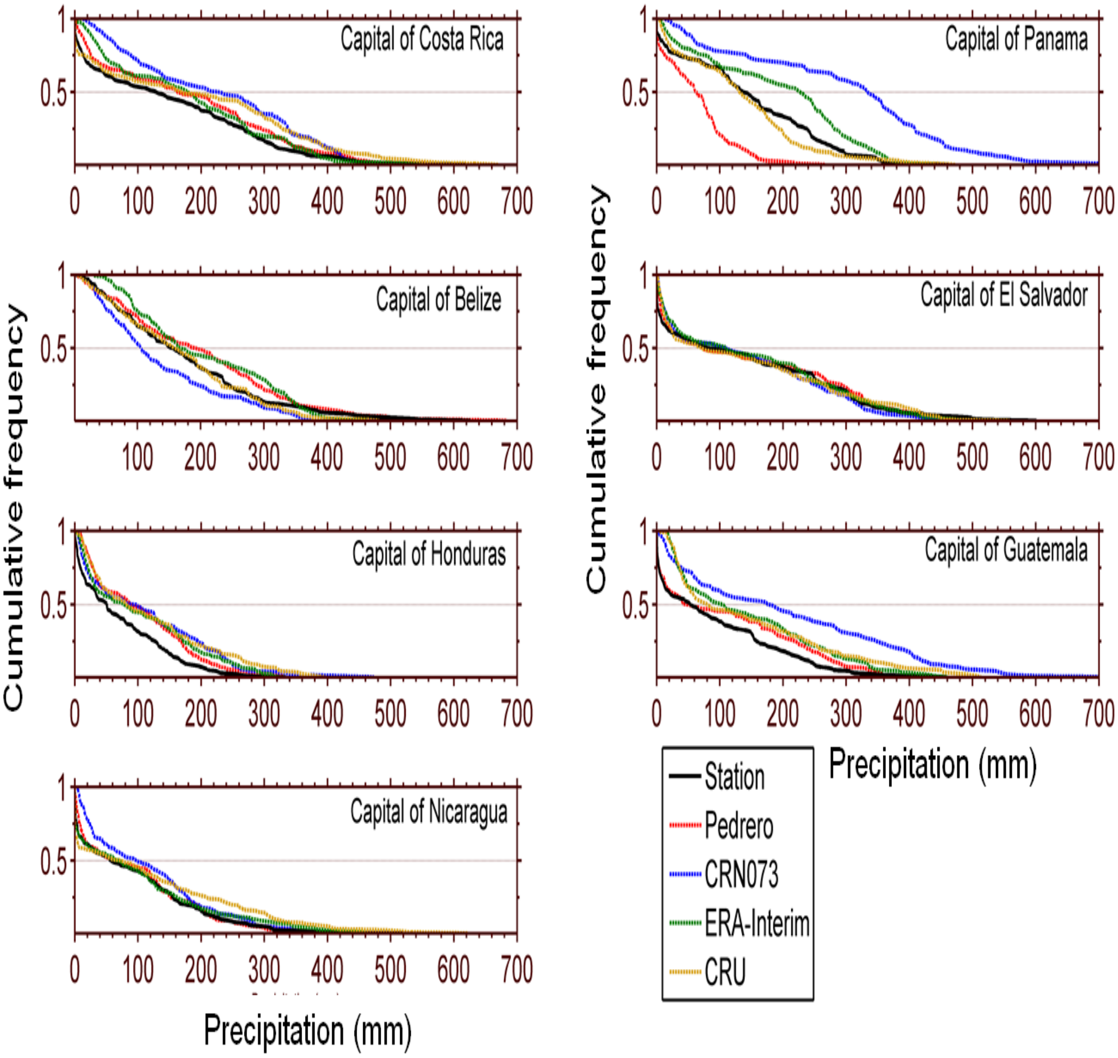

Figure 3: Distribution of precipitation (1979-1990) for the different datasets for the Central-American capitals

seismic and volcanic activity, besides it is constantly under the influence of tropical storms that develop in both the Caribbean Sea and Pacific Ocean, easterly waves and other climate variability features. However it is the interaction human-geophysical event, that transforms the occurrence of a natural hazard into what is commonly called a “natural disaster” (Alcántara, 2002; CEPAL, 2000). There are factors in the society that can aggravate the impact that the natural hazards have. It is important then to consider these aspects in the context of the Central American society.

Natural hazards have affected Central America through history taking lives and affecting society, environment and economy (Charveriat, 2000). The lack of risk reduction strategies has brought bad consequences. During the last decades the vulnerability to natural hazards has increased in the region as a consequence of the rapid and unplanned urban, industrial and demographic growth, environmental deterioration (due to the mismanagement of natural resources) and the poverty in both, rural and urban areas (BID, 2005; Mora, 1999; Mora and Keipi, 2006). Table 4 shows how a significant part of the population of Central America are

Country	Percent of Total Area at Risk	Percent of Populations in Areas at Risk
El Salvador	51.7	77.7
Costa Rica	38.2	77.1
Guatemala	28.8	69.4
Nicaragua	4.4	42.7
Honduras	18.1	31.8
Panama	2.6	5.1

Source: Dilley et al., 2005

Table 4: Central America countries at Relatively High Mortality Risk from Multiple Hazard

living in relatively high-mortality-risk areas from one or more hazards, all the countries of the region except Belize are among the top 35 countries (based on population) of the world having this characteristic (Dilley et al., 2005).

The Programa Estado de la región (2011) estimated that during the last decades Central America has experienced a rapid growth in its population, going from 17.1 million inhabitants in 1970 to 42.5 in 2010. The study also says that about two thirds of the population in Central America lives in urban areas, situation that result from having in these areas the concentration of infrastructure, services and higher possibilities for job and education. Unfortunately, this rapid urban growth has been unplanned, says the document. This situation causes many problems and sets a scenario hard to handle for the local governments. Among the problems are the big pressure that is put on resources (e.g. water) and services and the difficulty people have to find jobs. People with lower income have a hard time finding a piece of land where to live, so they are forced to group in non-formal settlements with problems of access to basic services and/or placed in risky areas like land-slide prone areas and flood plains (Salas-Serrano, 2007). The rural areas are affected as well, since these seem reduced even more the possibility of development due the migration of its population towards the urban areas.

The demographic and social chapters of the Programa Estado de la nación (2011) say the indigenous, women, young people and the disabled are groups that have multiple strong social gaps in Central America. Women are the ones taking care of the domestic duties and/or the children (receiving no salary for this) and working in average more hours and receiving less payment than men under the same work positions and conditions. The indigenous and people living in rural areas represent a group that has socio-economic disadvantages. These groups are lagged compared to the rest of the population in access to services such as health and education, drinking water and sanitation and labour market. Poverty seems to affect this groups harder as well.

An important fact on the long-term process of nature-induced disaster risk management is that even though some progress has been done in the past few years, the governments still prioritize mitigation, emergency and efforts in disaster response rather than reducing vulnerability (Mora, 2009). An example can be found in the study made by Christoplos et al.,

(2009) where they conclude that after the hurricane Mitch in Nicaragua “Risk reduction is on the national agenda and capacities for risk management have been greatly strengthened, but weaknesses remain in understanding vulnerability and in finding sustainable channels for local level risk reduction”.

There is still a lot to do in Central America in the subject of reducing vulnerability. Risk management has to be given more emphasis and should be seen as an investment, rather than a cost.

4 Models

4.1 Hydrological modelling: rainfall-runoff models

4.1.1 Brief Background

Hydrological models are simplified representations of the different parts of the hydrological cycle. They have been and continue to be, key tools in the understanding of the different hydrological processes. The beginning of the rainfall-runoff (RR) modelling dates back to the second half of the 19th century, they were developed to help solving three types of engineering problems: urban sewer design, land reclamation drainage systems and reservoir spillway design (Todini, 1988). Since then, RR models have continued to be developed even to the point that nowadays is very hard to name all the available hydrological models. Nowadays RR models are used in environmental science and engineering for a broad range of applications and even though they are just approximations, they are of great help in many decision making processes.

A RR model can be used for simulating for a certain catchment how does the total rainfall (it could also be snow, but for my purposes I do not consider this variable) translates into runoff. Therefore it models all the different processes (by representing them with mathematical equations) like infiltration of rainfall though the soil, determining when the soil is saturated and the interception of rainfall from vegetation, to name few. For this, the hydrological model needs input variables like precipitation, temperature and wind velocity, but depending on the model the need for input variables might vary.

The use of hydrological models have become a useful tool in the study of climate variability and climate change and have contributed in an important manner to a better understanding of climate and land-surface processes. As it was discussed before, there is a problematic with hydro-meteorological data availability in the region. For the case of hydrological data, hydrological models could be used to generate historical hydrological data (e.g. streamflow, soil moisture) in the Central American region. Having these data would allow to make climate variability studies. For example, if according to a certain precipitation-based drought index, a drought is taking place, one could use the simulated-historical streamflow data for that same period and region, and see how this drought event is captured by the hydrological data. The simulated hydrological data could also be used to find correlations between extremes (in the hydrological data) and climatic features that affect the region.

Hydrological models can also be used for forecasting purposes, so these models can be a valuable tool in the forecasting of events such as floods and (hydrologic)droughts.

4.1.2 Types of hydrological models (some examples of mostly used)

Hydrological models have been classified in several ways. One of them separates them according to the spatial description of the catchment processes. This results into lumped and distributed models:

- ***Lumped models*** consider the whole catchment to be a homogeneous unit, so that it assumes the same land characteristics and precipitation forcing data over the complete basin (an average value). This assumption does not occur in reality since precipitation, vegetation cover, soil type and other land characteristics vary in space.
- ***Distributed models*** on the other hand, do consider these spatial variations. To do this the basin is discretized into a network of grid points, each of these characterized by several parameters and variables (Refsgaard, 1997). This means, more parameters than for the case of lumped models, what due to the lack of distributed observations of runoff, can make the calibration methods time consuming and difficult (Ajami et al., 2004). The drawback of this "more realistic" approach is that high resolution data is needed and this is, in many cases, not so easy to obtain.

Models can also be linear or non-linear both in the systems theory or statistical regression sense.

Other classification is made depending on the way the models describe the hydrological process. Under this classification we can find the empirical, conceptual and physically based models.

- ***Empirical models*** (which can be also known as metric, data-based and black-box models) are the result of obtaining relationships between the input and output data (observations) with no understanding of the catchment behaviour and its flow processes. These models are in many of the cases spatially lumped (Wagener et al., 2004). Some examples of this type of models are the Artificial Neural Network (ANN), auto-regressive moving average model (ARMA).
- ***Conceptual models***: These models (also known as parametric, grey-box) do take into consideration the physical processes taking place in the catchment, but represent them in a rather simplified way. These models are built mainly using storage elements that are filled by rainfall, infiltration or percolation and emptied through evapotranspiration, runoff, and other processes (Wagener et al.,2004). A common configuration are the lumped conceptual models. Some of the common applications of these type of models, says the CLIMAWATER report (2009) are "for quality control and for filling of missing data, for extending historic flow records, generation of synthetic data runs for civil engineering design work, water resource assessment and management". The same report summarizes

some of the limitations of lumped conceptual models, among them the fact that the spatial heterogeneities are not represented by the averaged parameters. Other limitation pointed out by the study is that given the difficulty to find a good quality long historic record of data to calibrate the model, the biases that the observation data might have will be transferred to the parameter values. Other limitations are related to the fact that the models are calibrated for specific catchments and specific events, so changing these would mean that the optimal parameter set would also change. The interdependence of the model parameters and the fact that the model would probably not respond as good if these are changed, is another limitation these type of models have. Few examples of conceptual models are the water and snow balance modelling system (WASMOD)(Xu, 2002) and HBV (Bergström, 1976, 1992).

WASMOD: This model developed by Xu (2002) is, as said above, a conceptual lumped model and it calculates streamflow from snowmelt and rainfall. Input data for the WASMOD model include aereal precipitation, air temperature, humidity and potential evapotranspiration, but the latter can be estimated by the model if it is not available. Output data can be surface runoff, base flow, actual evapotranspiration (AET), soil water storage and snow accumulation. The model has three to six parameters depending on the climate of the region under study (i.e. there would be no snow-related parameters for a catchment in a tropical climate) and on the availability of input data and has time steps going from weekly to monthly. These parameters are a_1, a_2, a_3, a_4, a_5 and a_6.

Snowfall:

$$sn_t = p - t\left\{1 - e^{[(c-t-a_1)/(a_1-a_2)]^2}\right\}^+ \tag{12}$$

the sign + means $x^+ = max(x, 0)$

Rainfall:

$$r_t = p_t - sn_t \tag{13}$$

Snowmelt:

$$m_t = sp_{t-1}\left\{1 - e^{-[(c_t-a_2)/(a_1-a_2)]^2}\right\} \tag{14}$$

Snow:

$$sp_t = sp_{t-1} + sn_t - m_t \tag{15}$$

Parameters a_1 and a_2 are two threshold temperature parameters; snow starts melting when temperature is higher than a_2 and snow stops falling when air temperature is higher than a_1

Potential evap.:

$$ep_t = (1 + a_3(c_t - \tilde{c}))\bar{ep} \tag{16}$$

Actual evap.:

$$e_t = min\left\{ep_t(1 - a_4^{w_t/max(ep_t,1)}), w_t\right\} \tag{17}$$

or

$$e_t = min\left\{w_t(1 - e^{-a_4 ep_t}), ep_t\right\} \tag{18}$$

Parameters a_3 and a_4 are related to evapotranspiration

Slow flow:

$$s_t = a_5(sm_{t-1}^{+})^{b_1} \tag{19}$$

with $b_1 = 1$ or 2. Parameter a_5 is proportional to the amount of runoff that appears as base flow.

And fast flow:

$$f_t = a_6(sm_{t-1}^{+})^{b_2 n_t} \tag{20}$$

with $b_2 = 1$ or 2. Parameter a_6 is a fast flow parameter that is proportional to the degree of urbanization, average basin slope and drainage density.

Active rainfall:

$$n_t = p_t - ep_t[1 - e^{-p_t/max(ep_t,1)}] \tag{21}$$

Total runoff

$$d_t = s_t + f_t \tag{22}$$

Water balance

$$sm_t = sm_{t-1} + r_t + m_t - e_t - d_t \tag{23}$$

HBV: This lumped conceptual model was first developed in 1976 (Bergström) by the SMHI (Swedish Meteorological and Hydrological Institute). Many versions have been developed (Bergström, 1992; Lindström et al., 1997; Seibert, 1997, 2002 among others). The model input data are daily values of precipitation, air temperature and monthly estimates of potential evapotranspiration. Time step is usually daily, but shorter steps can also be used. The model contains several routines for snow accumulation and melt, soil moisture accounting, runoff generation and a simple routing procedure. The catchment is divided into zones depending on the altitude, lake area and vegetation (Harlin and Kung, 1992). Equations (taken from Harlin and Kung, 1992)

Snowmelt, $Q_m(t)$:

$$Q_m(t) = CFMAX \cdot [T(t) - TT] \tag{24}$$

where CFMAX is the degree-day factor, T is the mean daily air temperature and TT parameter, is the threshold temperature for snowmelt. Excess water from the soil, Q_s:

$$Q_s(t) = \left[\frac{S_{sm}(t)}{FC}\right]^{\beta} \cdot P(t) \tag{25}$$

Where S_{sm} is the soil moisture storage, FC is the soil saturation threshold parameter, P is the precipitation and β is the empirical coefficient.

$$E_a(t) \begin{cases} = \frac{E_p \cdot S_{sm}(t)}{LP}, & \text{if } S_{sm} \leq LP. \\ = E_p, & \text{if } S_{sm} > LP. \end{cases} \tag{26}$$

where E_a is the actual evapotranspiration, E_p is the potential evapotranspiration and LP is the S_{sm} threshold for E_p

Runoff generated from excess water from the soil and direct precipitation over open water bodies in the catchment area according to:

$$Q_u(t) \begin{cases} = S_{uz}(t) \cdot (K_0 + K_1) - K_0 \cdot UZL, & \text{if } S_{uz} > UZL. \\ = K_1 \cdot S_{uz}(t), & \text{if } S_{uz} \leq UZL. \end{cases} \tag{27}$$

where Q_u is the runoff generation from upper response tank, K_0, K_1, K_2 are recession coeficcients, UZL is the storage threshold between K_0 and K_1, S_{uz} is the storage in upper response tank, PERC is the percolation rate between the tanks, Q_1 is the runoff generation from the lower response tank and S_{lz} is the storage in lower response tank.

$$Q_1(t) = K_2 \cdot S_{lz}(t) \tag{28}$$

The continuity equations are

$$\frac{dD_{sm}}{dy} = P + Q_m - Q_s - E_a \tag{29}$$

$$\frac{dS_{uz}}{dt} = Q_s - Q_u - PERC \tag{30}$$

$$\frac{dS_{lz}}{dt} = PERC - Q_1 + P_1 - E_{pl} \tag{31}$$

where P_1 is the precipitation over lakes and E_{pl} is the potential evapotranspiration from lakes. HBV light, an easy-to-use version of the model for research and education has for example 11 parameters. TT,is a threshold temperature value for snowmelt, if it is overpassed all precipitation is rainfall and if it is below it then is snowfall. TT is multiplied by SFCF, a snowfall correction factor. CWH is another threshold value, if the fraction of meltwater and rainfall exceeds CWH value then is not retained any longer within the snowpack. FC is the largest value

- ***Physically based models*** (also known as theoretical, mechanistic) consider as well the physical processes and represent them using physically-based mathematical equations. A commonly used configuration is the distributed physically based model, that given its high complexity, has benefited from the rapid advance in computer power (Liu et al., 2007). These type of models were developed so that they could be used in applications that previous models could not tackle, or in other words, to overcome the limitations of previous models (like conceptual lumped) (Abbott et al., 1986). A debate about this being true though, can be found in the literature, for example Beven (1989), argues that distributed physically based models end up being conceptual lumped models, just that with more parameters. The conceptual leap, as he calls it, is made when applying the physically based equations at the grid-cell and using grid-cell parameter values, assuming with this that the grid cell is homogeneous, but lacking of a theoretical framework for doing this assumption. Besides, Beven comments that given the number of parameters that these models have, the problem of parameter interaction can even be greater than in the case of lumped models.

VIC: The Variable Infiltration Capacity model (Liang et al., 1994) developed by Xu Liang at the University of Washington, is a macroscale hydrologic model that solves for full water and energy balances. This model currently trying to be calibrated for the Central American region by researchers at Universidad de Costa Rica.

4.1.3 Calibration

As it has been discussed before hydrological models are simplified representations of the real processes. This means that we cannot reproduce the real system with exactitude, but our goal is to reproduce it as much as possible and model calibration can be a valuable tool for achieving this. The parameters in the models can be obtained either by direct measurements, or by calibration when the parameters cannot be measured. To clarify, that a parameter cannot be measured does not mean here that there are some physical limitations like lack of instruments or resources, but it means that they are immeasurable because they are just representing a feature of the basin after some concept, therefore lacking of physical interpretation. It can be the case as well, that even if the parameters could be measured, they need to be calibrated because of differences between the scales of the measurement or grid scale of the model and the scale from which the descriptions of the processes are derived (Madsen, 2003). The calibration procedure consists of trying to adjust the parameter values so that the simulations made by the hydrological model matches the real system (observations). Such procedure helps reducing the uncertainty in the simulations of the model by reducing parameter uncertainty (Cibin et al, 2010). The calibration procedure can be done manually or automatically (computer-based).

Manual Calibration: The calibration can be done manually, which consists of a semi-intuitive trial-and-error procedure and subject to the experience, training and understanding that the modeller has from the model structure (Boyle et al., 2000). Becoming skilled in manual calibration can take time since knowledge is mostly acquired with practice and it is hard to pass from person to person. After each "tuning" of the parameters, it is necessary to see how close are the predicted values to the observations. In a manual calibration, this is usually done through a visual inspection of the comparison of the plots of the predicted and observed values. In this way the parameter values can be changed until the modeller believes both plots are in good accordance.

Automated Calibration: Automated calibration was developed motivated by the fact that the calibration procedure should be less time consuming, also by the fact that there are not so many calibration experts and finally because it was considered to be a more objective way to estimate the parameters (Blasone et al., 2007). Automated calibration methods aim at finding the parameter values that minimize the distance between the predicted and observed values through some mathematical search algorithm. The process (adjusting parameter values, running the model, comparing predicted with observed values) is repeated until some criterion is satisfied, e.g. maximum number of model evaluations, convergence of the objective functions (see below), or convergence of the parameter set (Madsen, 2003). According to Gan and Biftu (1996) the quality of the automatic calibration procedure depends primarily in four factors:

model conceptual base and structure, power and robustness of the optimization algorithm, quality of data available (and whether it is informative or not) for the calibration and the estimation criteria and the objective function used in the optimization procedure (Gan and Biftu, 1996).

There are several goodness-of-fit measures used as a criteria to describe the goodness of the model simulations. These measures are commonly called *objective* functions, performance measures, fitness measures, likelihood measures or possibility measures and have been based in the past on the sum of squared errors or error variance (Beven, 2001).

Most commonly used (found in the literature) objective functions are found in table 5. Beven (2001) gives three reasons why these measures are not ideal for rainfall-runoff models. The first is that, since the residuals are squared, the calibration is done giving more weight to the high peaks. Other reason is that even if the shape and peak magnitude of hydrograph is well modelled, the residuals are going to be significantly large if the predicted and observed hydrographs are lagged in time. The third one is related to the assumptions that have to be made with these type of measures (independence and constant variance of the residuals), which are not always met. (Sorooshian and Dracup, 1980, also discussed about the cases when the assumptions on the residuals are not met and suggested using maximum likelihood theory to tackle this problem)

Name	Description	Formula
NS	Nash-Sutcliffe Measure	$1 - \dfrac{\frac{1}{n}\sum_{i=1}^{n}(O_i - P_i)^2}{\sum_{i=1}^{n}(O_i - \tilde{O})^2}$
RMSE	Root Mean Square Error	$\sqrt{\frac{1}{n}\sum_{i=1}^{n}((P_i - O_i)^2)}$
r^2	Coefficient of determination	$r^2 = \left(\dfrac{\sum_{i=1}^{n}(O_i - \tilde{O})(P_i - \tilde{P})}{\sqrt{\sum_{t=1}^{n}(O_i - \tilde{O})^2}\sqrt{\sum_{t=1}^{n}(P_i - \tilde{P})^2}}\right)$

Table 5: Table Commonly used objective functions

Where O_i and P are the observed and the predicted values, respectively and n, the number of observations. The Nash-Sutcliffe criterion value is in the range of $[-\infty, 1]$. The zero value means the model performs the same as in taking the average of the observed values. A NS value less than zero means the model performs worse than the average observed value. A value of one is a perfect fit. The r^2 ranges from 0 to 1, depending on how much the dispersion of the observed is explained by the simulations, with 1 meaning total correspondence and 0, no correspondence at all. RMSE ranges from $[0, \infty]$, with 0 representing a perfect fit.

It is important to have in mind that, as Gupta el at. (1998) say: "there is no real unambiguously "correct" way in which to define" objective functions and the selection of it can have a strong influence on the success of the model calibration (Sorooshian et al, 1983).

Recently, it has taken place a big development in multiple-objective automatic calibration procedures instead of based on a single objective function, since the latter is often not appropriate to measure how well the model simulates the characteristics of the observed data (Madsen, 2000; Yapo et al., 1998). The multi-objective calibration can generally be made based on multi-variable measurements, multi-site measurements and multi-response modes (Madsen et al., 2003). All the different objective functions have a different answer on which is the optimum parameter set, therefore in the multiple-objective calibration procedure the solution is a *Pareto optimal set*[1], instead of a unique set. Among the advantages of using this method is that the modeller performing the calibration can obtain information on model structural deficiencies and that it can provide a framework for different model and model-conceptualization comparisons.

Optimization algorithms

The plot of the objective function values against the parameters results in what is known as *response surface*. A big part the success of the optimization techniques is highly dependent on the objective function used and the nature of the response surface it generates (Sorooshian et al., 1983). The optimization algorithm looks where in the response surface is the optimum value (minimum or maximum, depending on the objective function used). For example, if the objective function used is the RMSE, in which a resulting value of 1 means that the model fits perfectly the observations, what one should search at the response surface are the valleys. In the automatic calibration the algorithms that search for the optimum (in the last example, minimum) values of the response surface are called *optimization algorithms*.

Optimization algorithms can be *local* or *global* (Sorooshian and Gupta, 1995, taken from Madsen and Jacobsen, 2001). Local can be classified into *direct* methods, which use only information from the objective function and the *gradient based* methods (not so used) which make use as well of the information about the gradient of the objective function (Beven, 2001). Some examples of local search methods, direct methods are the Simplex method (Nelder and Mead, 1965), pattern search method (Hooke and Jeeves 1961) and the Rosenbrock method (Rosenbrock, 1960).

The ideal situation is that there exists only one clear valley or peak in the response surface, but the reality is that the response surfaces have many local optima, valleys and plateaux, which are the result of the correlation between the parameters, the use of threshold parameters, heteroscedascity (no constant variance) and autocorrelation of the residuals, and of insensitive parameters (Beven and Binley, 1989). Duan et al. (1992) summarized the 5 main characteristics limiting a successful optimization algorithm in conceptual rainfall-runoff models: 1) regions of

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[1] Defined by Beven (2009) as "The set of models in a multi-objective evaluation that are not dominated by any other model on at least on one evaluation measure i.e. there is no model that performs better on that evaluation measure and on another evaluation measure (named after Vilfredo Pareto, 1848-1923, who originated the concept of Pareto efficiency in economics)"

attraction, where there is more than one convergence region 2) many local minima 3) roughness, rough response surface with discontinuous derivatives 4) sensitivity, poor varying sensitivity of response surface in region of optimum parameter interaction and 5) shape, nonconvex response surface with long curved ridges. All of these obviously complicates the work of the optimization algorithms because these can get confused and chose for example, one particular local minimum (and terminate the calibration procedure), or get "trapped" in the flat areas.

One might find it natural then to question about the effectiveness of the optimization algorithm and doubt if the optimum parameter set has really been found. The optimum found could actually depend on the starting point of the search in the response surface (Droogers and Immerzeel, 2006). This is why global search algorithms have been widely developed, since these methods search into the feasible parameter space. Among global search algorithms one can find the simulated annealing methods, genetic methods (Holland, 1975),the shuffled complex evolution algorithm, which combines hill-climbing techniques with genetic algorithms (Duan et al. 1992).

4.1.4 Sensitivity Analysis

Sensitivity analysis is a procedure that consists on finding out how sensitive is the model output to changes in the parameter values (Wagener et al., 2004). This analysis can be used to know about which parameters more knowledge is needed in order to improve the model, which parameters can be eliminated from the final model, which inputs contribute most to output variability, which parameters are most highly correlated with the output and what are the consequences of changing a certain input parameter, once the final models is being used (Hamby, 1994). If for example, through sensitivity analysis it is recognized that a parameter does not have a significant effect in the model output, this parameter could be then fixed to a certain value, reducing with this the number of parameters that must be estimated through the calibration process (Bastidas et al., 1999). Beven (2001) suggests that a reason why one may find an "insensitive" parameter could be because sometimes the parameters can be innsensitive in some range where they have not been "activated" during a run. The author gives the example of a parameter that represents the maximum storage capacity in a model, if this storage never gets filled, the parameter in that case is not "activated" so its value does not have that much impact in the model output. .

The sensitivity analysis can be done with respect to one of the predicted variables or to a certain performance measure (Beven, 2001). In general, sensitivity analysis techniques can be classified into two categories: local and global sensitivity analysis (GSA)(Pappenberger et al., 2008; Cibin et al., 2010). Local techniques (also known as one-at-a-time, OAT) consist of observing the model responses to varying each of the parameters individually while keeping the rest of the parameters constant. This method is widely used due to its simplicity, but has the limitation that assumes a linear relationship between the parameter and the output. According to Hamby (1994), one of the most fundamental sensitivity techniques is the *direct method*, which consists on calculating partial derivatives of the model with respect to an input parameter. The author, reviews the sensitivity index (among many others), which is a measure of how much the output changes with the variation of one input parameter (Hamby, 1994), calculated as:

$$SI = \frac{D_{max} - D_{min}}{D_{max}} \tag{32}$$

Where D_{max} and D_{min} are the resulting maximum and minimum output values from varying the input over its entire range. Other examples are the r Pearson coefficient and regression techniques. Just as in calibration, global techniques explore the entire range of parameter values and possible parameter sets (van Griensven et al., 2006). The regional sensitivity analysis (RSA, Hornberger and Spear, 1981), generalized sensitivity analysis (GSA) and the Hornberg-Spear-Young are examples of global methods for sensibility analysis.

4.1.5 Uncertainty Estimation

In many cases, models are used for predictions which in hand will be used for management and decision making. It is important to add to the model results some kind of information on how much we can trust the model results or in other words, how uncertain is our model. Uncertainty analysis consists on evaluating how uncertainties in the input and the model itself propagate onto the output.

According to Wagener et al.(2004) and Wagener and Gupta (2005) uncertainty in the hydrological modelling process has four major components:

- **Perceptual model uncertainty**: uncertainty resulting from what concepts are behind the model. This depends on our understanding of the real-world system.
- **Data uncertainty**: due to errors in the measurements of input and initial conditions and output data. The data errors come from measurement errors. Measurement errors can occur due to problems with the measuring devices or because of representativeness error (scale of measurement is different from what it represents in the model) (Liu and Gupta, 2007). In Central America for example, the lack of a good network of hydro-meteorological stations can introduce significant amount of uncertainty. In the Caribbean side for example, the scarcity of meteorologic stations (see figure 1) means that each point measurement is representing the average value of a relatively large area is actually heterogeneous. When using these data as input or for calibration and validation, these errors are introduced into the model and of course, will affect its output.
- **Model structural uncertainty**: this uncertainty is the result of the simplifications of the real processes that have to be made in order to have a model. These simplifications can be wrong simplifying and/or describing the processes inadequately and/or ambiguously.
- **Parameter estimation uncertainty**: because of the difficulty of finding a “best” parameter set based on the available information. Besides, the parameters are commonly estimated for a certain watershed and certain conditions (e.g. change of land use) and if either or both of the latter are changed, this could result in significant prediction uncertainty.

There are many methods available in the literature for uncertainty estimation. Westerberg (2011) points out the importance of stating clearly the assumptions made about the deviations between observed and simulated data and she names the frameworks under which these assumptions can be made, that is, Bayesian statistics, fuzzy sets and set-theoretic approaches. According to Beven (2009) the selection of one or another, depends on the type of problem to be tackled. The Bayesian Inference could be used for the cases in which a suitable error model can be determined (Westerberg, 2011). The Theorem of Bayes is:

$$p(A|X) = \frac{p(X|A) * p(A)}{C} \tag{33}$$

where $p(A|X)$ is the posterior distribution of the parameters, P(A) is the prior probability distribution of the parameters, $p(X|A)$ is the likelihood function of simulating the observations, X, given the model and C is a scaling constant. Assumptions have to be made about the error in order to get the likelihood function and in hydrology, this assumption is usually that the observations and the simulations are identical, independent and normally distributed (Yang et al. 2007a). According to Yang et al. (2007b) this assumption is commonly not met because of error in measurements of input and response, and errors in model structure that make the residuals to be heteroscedastic (no-constant variance) and autocorrelated. For the case in which it is not possible to find a suitable error model then, (hard to make assumptions about the error) fuzzy set-theory (Maskey et al., 2004) and set-theoretic approaches can be used. Among the set-theoretic approaches is the GLUE method.

The Generalized Uncertainty Estimation method, GLUE, is based on the concept of equifinality (Beven and Binley, 1992; Beven, 1993, 1996), defined by Beven (2001) as “the concept that there may be many models of a catchment that are acceptably consistent with the observations available “. The idea is to assign a certain degrees of “believe” to different parameter sets. In this method, based on Monte Carlo simulations, a large number of runs are made by using different sets of parameter values, which are selected randomly from a specified parameter distribution. Each of these set of parameter values is assigned a likelihood measure (a-goodnes-of-fit criterion) according to the comparison between the predicted and the observed values over a calibration period, so that those that are below a certain threshold are said to be “non behavioural” and are discarded (Beven and Binley, 1992; Beven, 2001; Stedinger et al., 2008). The method has been criticized from using subjective likelihood measures and not using a formal representation of model error (Beven, 2006;). Stedinger et al. (2007) also name some of the criticisms the method has received from the study of Kuczera and Parent (1998) that points out the large demand of computer power it has.

An application of the method was made by Westerberg et al. (2010) for the Paso La Ceiba catchment in Honduras. The authors developed a calibration method using flow-duration curves (FDCs) for the WASMOD model. The FDCs method aims at reproducing the frequency distribution of the observed discharge instead of at reproducing the exact hydrograph. GLUE limits of acceptability for the observed FDCS were applied for some selected evaluation points, so simulations could be defined as behavioural or not. The method worked well specially in the calibration of slow flow, recession and evaporation.

A lack of a good hydro-meteorological network for measurements in the case of Central America will affect the quality of hydrologic and atmospheric modelling in that region, therefore it is important to always have an uncertainty analysis accompanying modelling studies. Specially if these studies will weight in decision making and management processes.

4.2 Atmospheric models

Atmospheric general circulation models or AGCMs or GCMs, where initially developed in the decade of the 1960, among them GFDL, UCLA and NCAR models. These models use the equations of compressible fluids and adiabatic processes to simulate the physical and dynamic processes that occur around the globe (Amador and Rivera, 2008). For example, these models are able to capture features like the ITCZ, jet-streams and the Hadley cells. GCMs are used for weather forecasting, for the understanding of climate and for the prediction of climate change. When atmospheric GCMs are coupled with oceanic GCMs they result into a *climate model*.

To solve all the different atmospheric processes, the globe is covered by a three dimensional grid, so that the calculation of the physical and dynamic processes are done at every grid cell taking into account also, the interactions among them. Every grid cell covers an area of the order of hundreds of kilometres in the horizontal. This requires a considerable amount of data and computer power to cover the whole world and it means that the smaller the grid cell is, the more the interactions between grid cells and the more the number of times the calculation of the processes have to be computed. This puts a limitation on how small the grid cell can be, therefore on the applications of the GCMs. The scale of the GCMs is too coarse for the scale needed for studying climate impacts at a local scale. For this reason, different techniques to reduce the scale of the GCMs have been developed under the name of *downscaling* techniques. Such techniques must be applied to GCM output to do studies of climate variability and its impacts in Central America, since the region has an area of 530 492 km^2. A deeper description of such techniques and some examples are given in the next subsection.

Atmospheric models can be used to generate the meteorological data that unfortunately is not available. These models can both, generate historical data and future data for forecasting purposes. Since the hydrological models need of meteorological data as input, it is clear the importance that atmospheric models have.

4.3 Downscaling Climate Data

GCMs, as it was commented on the previous subsection, are a very important tool for the study of climate variability. But there is a computational limitation on the spatial resolution that these models can be run, which can be in some cases not enough for regional-scale applications (in the order of tens of kilometres) (Huth, 1999; Zorita and Storch, 1999; Amador and Rivera, 2008; Lo et al., 2008). One example of an application that would be limited by the resolution of the GCM meteorological data is the study of the hydrological impact if climate change under different scenarios (Wilby and Wigley, 1997; Xu, 1999; Wood et al., 2004; Haylock et al., 2006). In particular, for the application of hydrological models in Central America, the resolution of the GCM meteorological data is too low to represent the large variability of the region.

For these reason several methods have been developed and could be applied to take the GCMs output into a smaller scale. Such process is called *downscaling* and it has been separated into two broad classifications: dynamical and statistical downscaling. Neither of each has been found to be better than the other.

An important thing to have in mind when working with data from GCMS is that these data suffer from systematic biases that should be corrected (Wood et al., 2002). The downscaling is of course, strongly influenced by these biases, therefore several *bias correction* methods have been developed to improve the downscaling of the climate data (Xu et al, 2012). A common technique that has is used, including in studies in Central America is the Bias Correction and Spatial Downscaling method (BCSD; Wood et al., 2004).

4.3.1 Statistical downscaling

Wetterhall (2005) defines statistical downscaling “as the creation of a relationship between the large-scale circulation (predictors) and the local weather variables (predictands)”. Among the advantages of statistical downscaling are that it is not computationally demanding and it can be easily adjusted to new areas (Wetterhall,2005). Some common methods used for statistical downscaling are:

Analogues methods: The analogues method consists of finding, for one particular state of the atmosphere, an analogue or identical (within some error range of acceptance) state from a set of historical observations. The analogues method has been widely used in meteorology for weather forecasting and short-term climate predictions (Lorentz, 1969; Van den Dool, 1994) and also as a downscaling technique (Zorita et al., 1995; Hidalgo et al., 2008). The idea is to find in a historical data of observation the most similar (an analogue) to the pattern of the GCM output, then, that observation is associated with the large scale weather pattern (Zorita and Von Storch, 1999). Under this method is the constructed analogues method, which instead of searching for a single analogue it constructs it by making a linear regression with a number of analogues from the historical record. The advantage of the analogues technique is that its computational costs are low and is a simple and straightforward method, the disadvantage is that it requires of a long historical record of data to cover all the different climates including extremes (Fernández and Sáenz, 2003). I applied the constructed analogues method for the Central American region for my master thesis. Unfortunately, the results were not satisfactory and the quality of the downscaled data was not better than that of the coarser scale data.

Regression methods: Wilby and Wigley (1997) describe these methods as those that “involve establishing linear or non-linear relationships between subgrid-scale (e.g. single-site) parameters and coarser resolution (grid-scale) predictor variables”. Among these methods can be found Canonical Correlation Analysis (CCA,, principal component analysis, neural networks and composition technique.

Principal Component Analysis (PCA) also known as *empirical orthogonal function* (EOF) for example, is a multivariate analysis technique that aims at reducing the dimensionality of the dataset by making linear combinations that contain as much as possible of the variability of the data (Wilks, 1995). CCA is another commonly used multivariate analysis technique that allows to get interrelationships among sets of multiple dependent variables and multiple independent variables (instead of just one single dependent variable as in the case of multiple regression)(Wilks, 1995).

Like is mentioned in Amador and Alfaro (2009), in the Central American methods such as CCA (Soley and Alfaro, 1999; Alfaro, 2007 a,b), Single Value Decomposition (DVS)(Enfield and Alfaro, 1999; Alfaro 2007a,b), EOF (Alfaro, 2002), Vector Autoregression Moving-Average (VARMA)(Alfaro and Cid, 1999; Alfaro and Soley, 2001) and linear regression (Alfaro, 2002; Alfaro and Amador, 2003) have been applied.

4.3.2 Dynamical downscaling

Dynamical downscaling is done by driving a high-resolution model into the low-resolution GCM or global reanalysis (Amador and Alfaro, 2009). This immerse or "nested" model is called Limited Area Model (LAM) or when it comes to climate time scales, Regional Climate Model (RCM) and uses the information from the coarse-resolution model as initial, and lateral meteorological and surface boundary conditions (Lo et al., 2008). The idea is to add more detailed information at a smaller grid-size and with that, capture some regional scale forcing like the one induced by the interaction of topography, coastlines and land use/land cover with the predominant flow (Lo et al., 2008; Amador and Alfaro, 2009). The advantages of this method is that it takes into account the physical and dynamical aspects of the system (Amador and Alfaro, 2009). The disadvantages are the extensive computational power required by this type of downscaling and the effects that can have the systematic errors in the information coming from the global models (IPCC Report, 2001).

One of the challenges do deal with when doing a dynamical downscaling exercise is the choice of the different physics parametrisation, model domain size and resolution, the technique chosen for assimilation of the large-scale meteorological conditions and the internal variability caused by the non-linear dynamics (IPCC Report, 2001).

In Central America, dynamic downscaling has bees been implemented in some studies, such as the ones by Rivera and Amador (2008;2009) have evaluated the downscaling using the CCM3.6 and the MM5v3. More studies about the appropriate parametrisations of different LAMs for the Central American region are needed, since most of the studies have been done in higher latitudes where the atmospheric processes are not the same. Currently, the CNDS student Tito Maldonado is dedicating his research to this area, researching on which configuration (parametrisations, domains) suits better for the region. There is, therefore a big importunity for collaboration between us two.

Table 6 summarizes the advantages and disadvantages between the statistical and the dynamical downscaling. As it can be seen, neither of these methods is considered to be the best. Selection should depend on factors like computer power availability, quantity and quality of the data, time to perform the study, among others.

	Statistical downscaling	Dynamical downscaling
Advantages	- Comparatively cheap and computationally efficient - Can provide point-scale climatic variables from GCM-scale output - Can be used to derive variables not available from RCMs - Easily transferable to other regions - Based on standard and accepted statistical procedures - Able to directly incorporate observations into method	- Produces responses based on physically consistent processes - Produces finer resolution information from GCM-scale output that can resolve atmospheric processes on a smaller scale
Disadvantes	- Require long and reliable observed historical data series for calibration - Dependent upon choice of predictors - Non-stationarity in the predictor-predictand relationship - Climate system feedbacks not included - Dependent on GCM boundary forcing affected by biases in underlying GCM	- Computationally intensive - Limited number of scenario ensem bles available - Strongly dependent on GCM bound ary forcing

Source:Fowler et al., 2007

Table 6: Advantages and disadvantages of dynamical and statistical downscaling

4.4 Coupling an atmospheric model with a hydrological model

Coupling is the process where a model receives the output from another model as its input. The coupling is done following the idea that in the real system, the atmosphere and surface are in constant interaction, so if the models representing the different processes (atmospheric and surface) are interacting with each other, just like the real system, the results might be closer to reality. The coupling can be done in two ways: one-way where the hydrological model receives as input the output of the atmospheric model (e.g. Yu et al., 1999; Hay et al., 2006;) and the two-way, where the hydrological model besides receiving the input, gives back its output to the atmospheric model, resulting in a two way interaction system. Even though many attempts of coupling can be found in the literature, many limitations have been found like inconsistency in the parametrisations of the physical processes, problems due to numerical compatibility, and the computer-power limitation (Bindlish and Barros, 2000).

With the coupling of these models, the hydrological model can translate the output of the atmospheric model to basin level runoff, streamflow, soil moisture, among others. Impact in water availability due to climate change, runoff estimation for flood forecasting (to name few), are studies that can be done by coupling a hydrological model with an atmospheric model.

Basically, what is wanted with this approach is to model more appropriately the water cycle (Mölders and Raabe, 1997). There are still many challenges with the implementation of this coupled systems, specially due to the difference of the spatial resolutions at which each of the models operate (Bindlish and Barros, 2000; Seuffert et al., 2002). The spatial and temporal scale of the hydrological models, compared to those of the atmospheric models, allow longer time steps, but need of much finer grids (Mölders and Raabe; Seuffert et al., 2002). GMS have too coarse resolution for the basic scale hydrological modelling, therefore downscaling is necessary (Hay et al., 2002).

Some examples of one-way coupling can be found in the literature, most of them concluding the "unripe" state of the development of this system and many conclude that biases from the atmospheric models should be corrected. For example, Hay et al. (2006), did one-way coupling of the Pennsylvania State University-National Center for Atmospheric Research Mesoscale Model (MM5) and the U.S. Geological Survey's distributed and they found that this configuration was not as good as running the hydrologic model with climate station data. Bartholmes and Todine (2005) used a one-way coupled system for flood forecasting in the River Po in Italy, trying to extend it to a time where water authorities can implement emergency plans for downstream areas (between one and four days in advance). The models used were the TOPographic Kinematic APproximation and Integration (TOPKAPI) and weather forecast coming from the European Centre for Medium Range Weather Forecast (ECMWF), the German Weather Service (DWD) and the Danish Hydrological Institute (DMI) and it was concluded that there is still improvement to do on the meteorological side. A different application was done by Benoit et al. (2000) by using the one-way coupling as a complementary tool to validate the atmospheric model, the authors found with the help of the WATFLOOD, that in fact increasing the spatial resolution of the MC2 atmospheric model improved the atmospheric simulations. Hay et al. (2002) found that after a bias correction to climate data from the RegCM2, improved the runoff simulated by the Precipitation Runoff Modeling System (PRMS) hydrological model.

Coupling atmospheric and hydrologic models is still being developed. Many obstacles have to be overcome when it comes to the different time and space resolutions and inconsistency of parametrisation. Hopefully with more studies accompanied of a constant increase in computer power, a successful coupled system can soon be possible.

5 Current and future work

As I described on the introduction of this introductory report the subject of study during my PhD is variability of climate and water resources in Central America. Currently I am the first author of the -to be published article:

- Quesada Montano, B., Westerberg, I. K., Hidalgo, H., Wetterhall, F., Halldin, S., Lundin, L-C. Spatial and temporal characterization of droughts in Central America: evaluation of five drought indices. Manuscript (Plan to be published in 2013).

In this study we evaluated five drought indices in terms of how good they characterize the spatial and temporal variability of droughts in the Central American region. The best-performing indices could hopefully be used in future studies like e.g. to find correlations with oceanic and/or atmospheric features such as El Niño Southern Oscillation (ENSO), for climate change impacts studies and eventually for forecasting drought events (useful in water management planning or in agriculture). A secondary objective of the study was the evaluate different meteorological datasets. For this, we calculated the various drought indices using the different datasets. This allowed us to do an examination of their capability to represent the complex climate of the region, such an evaluation has never been done before. A poster about this study was presented at the European Geophysical Union conference in the spring of the current year and possibly the same will be done at the American counterpart of the same meeting (American Geophysical Union) next winter. My plan is to continue assisting to conferences and meetings every year as a way to improve my work, learn about new methods within my field of research and start creating my research network.

I collaborated with:

- Juston, J., Kauffeldt, A., Quesada Montano, B., Seibert, J., Beven, K. and Westerberg, I. Smiling in the rain: Seven reasons why to be positive about uncertainty in hydrological modeling. Invited Commentary. Submitted to Hydrological Processes, October, 2012.
- Hidalgo, H., Amador, J., Alfaro, E. and Quesada Montano, B. Hydrological Climate Change Projections for Central America. Manuscript, 2012.

Place where I will develop my research: The Central American counterpart of CNDS, CANDIM, is under what is called a "sandwich" model. This means that each student spends every year a part in Sweden and another part at their home universities. I plan to follow this model and go every year to Costa Rica and work during my stay there in collaboration with my Costa Rican supervisor at the Universidad de Costa Rica. By going to Costa Rica it would facilitate me the access to data and the direct contact with researchers doing (or that have done) similar studies in Central America.

Courses: I consider taking courses relating hydrological modelling, downscaling of meteorological data, and nature induced disasters caused by extreme hydro-meteorological events. I have taken the following courses:

- Geoinformatics, Uppsala, Spring, 2011.
- Introduction to natural disaster science, Uppsala, Autumn, 2011.
- Catchment Science Summer School. Aberdeen, August, 2011.
- Uncertainty in Environmental Modelling. Uppsala, June, 2010.

Other duties: I intend to be involved with teaching during the coming years, since capacity building is one of the aims within CANDIM. For this, I plan to take the "Academic teacher training course" during the spring of 2013.

Expected date of defence: the preliminary data for the PhD defence is 20th of April of 2016. I have also planned to have a licentiate degree, for which I plan to defend around the 4th of April of 2014.

REFERENCES

Abbot M. B., Bathurst J. C., Cunge J. A., O'Connell P. E., Rasmussen, J. 1986. An introduction to the European Hydrological System - Systeme Hydrologique Europeen 'SHE' 2. Structure of the physically based, distributed modelling system. J. Hydrol. 87, 61-77.

Aguilar E., et al. 2005. Changes in precipitation and temperature extremes in Central America and northern South America, 1961-2003, J. Geophys. Res., 110, D23107, doi:10.1029/2005JD006119.

Ajami N.K., H.V. Gupta, T. Wagner, S. Sorooshian.2004. Calibration of a Semi-Distributed Hydrologic Model for Streamflow Estimation along a River System. J. Hydrol. 298(1-4): 112-135, doi: 10.1016/j.hydrol.2004.03.033, Oct. 2004

Alcántara-Ayala, I. 2002. Geomorphology, natural hazards, vulnerability and prevention of natural disasters in developing countries. Geomorphology, 47: 107?24.

Alfaro E. 2002. Some characteristics of the annual precipitation cycle in Central America and their relationships with its surrounding tropical oceans. Top. Meteor. y Oceanograf. 7(2), 99-115

Alfaro E., Amador J. 1997. Variabilidad y cambio climático en algunos parámetros sobre Costa Rica y su relación con fenómenos de escala sinóptica y planetaria. Top. Meteor. Oceanogr. 4(1), 51-62

Alfaro E., Cid L. 1999. Ajuste de un modelo VARMA para los campos de anomalías de precipitación en Centroamérica y los índices de los océanos Pacífico y Atlántico Tropical. Invest. Mar., Valparaíso, 26, 59-69.

Alfaro E., L. Cid, D. Enfield. 1998. Relaciones entre el inicio y el término de la estación lluviosa en Centroamérica y los Océanos Pacífico y Atlántico Tropical, Invest. Mar., Valparaíso, 26.

Amador J. 1998. A climatic feature of the tropical Americas: The trade wind easterly jet. Top Meteor. Oceanogr. 5(2):1?13

Amador J. 2009. Métodos de reducción de escala: aplicaciones al tiempo, clima, variabilidad climática y cambio climático. Revista Iberoamericana de Economía Ecológica. 11,39-52.

Ártigas R. 2003. The Case of the Trifinio Plan in the Upper Lempa: Opportunities and Challenges for the Shared Management of Central American Transnational Basins. UNESCO-IHP, PCCP Series Publication, 13 p.

Bartholmes J, Todini E. 2005. Coupling meteorological and hydrological models for flood forecasting. Hydrology and Earth System Sciences 9: 333?346

Basterrechea, 2012.Estado del agua en Guatemala. In: Jiménez B., Galizia J. Diagnóstico del agua en las Américas.

Bastidas, L.A., Gupta, H.V., Sorooshian S., Shuttleworth W.J., Yang Z.L. 1999. Sensitivity analysis of a land surface scheme using multi-criteria methods. J. Geophys. Res.104, 19-481-19,490.

Benoit, Robert, Pierre Pellerin, Nick Kouwen, Harold Ritchie, Norman Donaldson, Paul Joe, E. D. Soulis, 2000: Toward the Use of Coupled Atmospheric and Hydrologic Models at Regional Scale. Mon. Wea. Rev., 128, 1681?1706.

Below, R., Grover-Kopec, E., and Dilley,M. 2007. Documenting drought-related disasters: a global reassessment, J. Environ. Develop., 16, 328?344, http://dx.doi.org/10.1177/1070496507306222doi:10.1177/1070496507306222, 2007.

Bergström, S. 1976. Development and application of a conceptual runoff model for Scandinavian catchments. Ph.D. Thesis. SMHI Reports RHO No. 7, Norrköping.

Bergström, S. 1992. The HBV model - its structure and applications. SMHI Reports RH, No. 4, Norrköping.

Beven K.J., 2009. Environmental Modelling: An Uncertain Future? Routledge, London.

Beven K. J. 2006. A Manifesto for the Equifinality Thesis. J.Hydrol. 320 (1-2). pp. 18-36.

Beven K.J. 2001. Rainfall-runoff modelling? the primer. John Wiley & Sons Ltd, London. pp. 234-235, 317.

Beven K. J. 1989. Changing ideas in hydrology-the case of physically based models, J. Hydrol., 105, 157?172.

Beven K.J., and Binley, A.M. 1992. The future of distributed models: model calibration and uncertainty prediction: Hydrological Processes. v. 6, p.279?298.

BID (Banco Interamericano de Desarrollo). 2000. El desafío de los desastres naturales en América Latina y el Caribe: Plan de Acción del BID, Washington, D.C., United States.

Bindlish R., Barros A.P. 2000. Disaggregation of rainfall for one-way coupling of atmospheric and hydrologic models in regions of complex terrain. Global Planet. Change, 25, 111?132.

Blasone R. S., H. Madsen, Rosbjerg D. 2007. Parameter estimation in distributed hydrological modelling: comparison of global and local optimisation techniques. Nordic Hydrology. 38, 451-450.

Boin A., t'Hart P. 2010. Organising for Effective Emergency Management: Lessons from Research. Australian Journal of Public Administration (December 2010), 69 (4), pg. 357-371

Boyle D.P., Gupta H.V., S. Sorooshian, V. Koren, Z. Zhang, and M. Smith, 2001. Towards improved streamflow forecasts: The value of semi-distributed modeling. Water Resources Research, AGU, 37(11), 2749-2759,

Brenes T. 2010. Elementos constitutivos del riesgo de sequía en América Central. La irregularidad y el acceso al suelo. En E. Mansilla 2010. Global Assessment Report on Disaster Risk Reduction. Geneva, Switzerland: UNISDR. Chapter 1.

Brentlinger P. E., Hernán M. A. 2007. Brentlinger PE, Hernán MA. Armed conflict and poverty in Central America: the convergence of epidemiology and human rights advocacy. Epidemiology 18(6), 673-7.

Byun, H. R.; Wilhite, D. A. 1999. Objective quantification of drought severity and duration. J. Climate 12, 2747?2756

Caballeros R., Zapata R., Mora S. Seminar "Confronting Natural Disasters: A Matter of Development". New Orleans, 2000. ECLAC and BID.

Centro de Coordinación para la Prevención de los Desastres Naturales en América Central (CEPREDENAC). 2010. Política Centroamericana de gestión integral de riesgo de desastres. Reunión ordinaria de jefes de estado y gobierno de los países del Sistema de la Integración Centroamericana (SICA). Panamá

CEPAL. 2005. Los recursos hídricos y la agricultura en el istmo centroamericano. CEPAL, UN. México DF.

CEPAL. 2000. Panorama del impacto ambiental de los recientes desastres naturales en América Latina y el Caribe. Documento preparado para el Comite Tecnico interagencial del Foro de Ministros de Medio Ambiente de America Latina y el Caribe, 23 de febrero de 2000, PNUMA, Mexico, D.F., Mexico.

CEPAL/IDB. 2000. A Matter of Development: How to Reduce Vulnerability in the Face of Natural Disasters. ECLAC, Mexico DF.

Charvériat C. 2000. Natural Disasters in Latin America and the Caribbean: An Overview of Risk. IDB Working Paper No. 364. Available at SSRN:
http://ssrn.com/abstract=1817233 or http://dx.doi.org/10.2139/ssrn.1817233

Cibin R., Sudheer K.P., Chaubey I. 2010. Sensitivity and identifiability of stream flow generation parameters of the SWAT model. Hydrol. Process. Published online in Wiley InterScience (www.interscience.wiley.com)
DOI: 10.1002/hyp.7568. p.1133-1148

CLIMAWAT. 2009. Hydrological Modelling-Literature Review. Report No. 1. Bioforsk, Norway, IIT, Delhi.

Chiew F.H.S., McMahon T.A. 2002. Global ENSO-streamflow teleconnection, streamflow forecasting and interannual variability. Hydrological Sciences Journal, 47: 505-522.

Congressional Research Service, The Library of Congress, CRS Report for Congress, Hurricane Katrina: Social-Demographic Characteristics of Impacted Areas, November 4, 2005

Christoplos I., Rodriguez T., Schipper L., Narvaes E. A., Bayres K. M., Buitrago R., Gómez L., Pérez F. J. 2009. Learning from Recovery after Hurricane Mitch: Experience from Nicaragua. International Federation of Red Cross and Red Crescent Societies / the ProVention Consortium PROVENTION Consortium

Díaz H.F., Markgraf V. 2000. El Niño and The A Southern Oscillation: Multiscale Variability and Global Regional Impacts. Cambridge University Press, Cambridge, UK. pp.4.

Dilley M., Chen R.S., Deichmann U., Lerner-Lam A.L., Arnold M. 2005. Natural Disaster Hotspots. A Global Analysis. The World Bank and Hazard Management Unit. Washington D.C. pp. 2, 8.

Ding Y., Hayes M. J., Widhalm M. 2010. Measuring Economic Impacts of Drought: A Review and Discussion. Papers in Natural Resources. Paper 196. Available at: http://digitalcommons.unl.edu

Dimas L. 2005. La situación del recurso hídrico en El Salvador. Sistema de Información Económica (SIE). Boletín 235.

Droogers P., Immerzeel, W. 2006. Calibration Methodologies in Hydrological Modeling: State of the Art, Future Water Report 56,
http://www.futurewater.nl/ krishna/results.html.

Duan Q., Sorooshian S., Gupta V. 1992. Effective and efficient global optimization for conceptual rainfall-runoff models. Water Resources Research, 28(4), 1015-1031

EM-DAT Glossary. The OFDA/CRED International Disaster Database ? www.emdat.be, Université Catholique de Louvain, Brussels (Belgium)

Enfield D.B. 1996. Relationships of inter-American rainfall to tropical Atlantic and Pacific SST variability. Geophys. Res. Lett.,23, 3305?3308.

Enfield D.B., Alfaro E. 1999. The dependence of Caribbean rainfall on the interaction of the tropical Atlantic and Pacific Oceans, Journal of Climate,12.

Enfield D.B., Mayer D.A. 1997. Tropical Atlantic SST variability and its relation to El Niño-Southern Oscillation. J. Geophys. Res.,102, 929?945.

Fernández J., Sáenz J. 2003. Improved field reconstruction with the analog method: searching the CCA space, Clim. Res. 24:199-213.

Food and Agriculture Organization (FAO). 2011. Glossary. Extracted online from:
http://www.fao.org/docrep/005/Y4473E/y4473e04.htm

FAO-AQUASTAT -2011. Water resource information by country/territory and MDG Water Indicator. Available at:
http://www.fao.org/nr/water/aquastat/maps/AQUASTAT_water_resources_and_MDG_water_indicator_November_2011.pdf

Fowler H. J., Blenkinsop S., Tebaldi, C. 2007. Linking climate change modelling to impacts studies: recent advances in downscaling techniques for hydrological modelling. Int. J. Climatol., 27: 1547?1578. doi: 10.1002/joc.1556

Freeman P., Martin L.A., Linneroot-Bayer J., Mechler R., Pflug G., Warner K. 2003. Disaster Risk Management: National Systems for Comprehensive Management of Disasters Risk and Financial Strategies for Natural Disaster Reconstruction. Inter-American Development

Bank, Sustainable Development Department/Integration and Regional Programs Department, Regional Policy Dialogue, Washington, D.C.

Gan T. Y., G. F. Biftu. 1996. Automatic Calibration of Conceptual Rainfall-Runoff Models: Optimization Algorithms, Catchment Conditions, and Model Structure, Water Resour. Res., 32(12), 3513?3524, doi:10.1029/95WR02195

Giannini A., Kushnir Y., Cane M. 2000. Interannual variability of Caribbean rainfall, ENSO and the Atlantic Ocean. J. Climate, 13, 297-311.

Global Water Partnership (GWP). 2003. Status of national integrated water resources management processes in Central America. GWP, Central America. Guanacaste.

Global Water Partnership (GWP). 2011. European Union, Programa de Desarrollo de Zonas Fronterizas en América Central, Banco Centroamericano de Integración Económica. Situación de los recursos hídricos en Centroamérica. Hacia una gestión integrada. GWP Centroamérica. Tegucigalpa.

Gray W. 1984. Atlantic Seasonal Hurrican Frequency. Part I: El Niño and 30 mb Quasi-Biennial Oscillation Influences. Mon. Wea. Rev. 112, 1649-1668.

Gupta H.V., Sorooshian S. 1985. The Automatic Calibration of Conceptual Catchments Models Using Derivative-Based Optimization Algorithms, Water Resources Research, Vol. 21, No. 4, pp. 473-486.

Hamby D.M. 1994. A Review of Techniques for Parameter Sensitivity Analysis of Environmental Models. Environmental Monitoring and Assessment. Vol. 32 (2), 2 135-154.

Harlin J., Kung, C. 2002. Parameter uncertainty and simulation of design floods in Sweden, J. Hydrol., 137, 209?230.

Hastenrath S. L. 1967. Rainfall distribution and regime in Central America, Theor. Appl. Climatol., 15, 201?241, doi:10.1007/BF02243853.

Haug G. H., Günther D., Peterson L. C., Sigman D. M. , Hughen K. A., Aeschlimann B. 2003. Climate and the collapse of Maya civilization. Science 299,1731-1735.

Hay L.E., Clark M. P., Pagowski M. , Leavesley G. H., Gutowski W. 2006. One-Way Coupling of an Atmospheric and a Hydrologic Model in Colorado. Journal of Hydrometeorology 7(4), 569-589

Hay L.E., Clark M. P., Wilby R. L., Gutowski W. J., Leavesley G. H., Pan Z., Arritt R. W., Takle E. S. 2002. Use of regional climate model output for hydrologic simulations. J. Hydrometeor., 3, 571?590.

Hayes M.J., Svoboda M.D., Wilhite D.A., Vanyarkho O.V. 1999. Monitoring the 1996 drought using the standardized precipitation index. Bull. Am. Meteorol. Soc. 80(3): 429-438

Hidalgo H. G., Dettinger M. D., Cayan D. R. 2008. Downscaling with constructed analogues: daily precipitation and temperature fields over the United States, California Energy

Commission, Public Interest Energy Research Program, Sacramento, CA, 62.

Hidalgo H. 2012. Los recursos hídricos en Costa Rica: un enfoque estratégico. In: Jiménez B., Galizia J. Diagnóstico del agua en las Américas.

Hodell D. A., J. H. Curtis, Brenner M. 1995. Possible role of climate in the collapse of Classic Maya civilization. Nature 375:391-394.

Hooke R., Jeeves T.A. 1961. Direct search solution of numerical and statistical problems. Journal of the Association for Computing Machinery (ACM) 8 (2), 212-229.
doi:10.1145/321062.321069

Hurtado I., Picado F., Flores Y., Calderón H., Delgado V., Flores S., Caballero Y., Jiménez M., Sáenz R. 2012. Recursos hídricos en Nicaragua. Una visión estratégica. In: Jiménez B., Galizia J. Diagnóstico del agua en las Américas.

Inter-American Development Bank. 2007. From disaster response to prevention. Companion paper to the disaster risk management policy. Sector Strategy and Policy Paper Series. Washigton, D.C.

Inter-American Development Bank. 2005. Gestión de riesgo de amenazas naturales en proyectos de desarrollo. Lista de preguntas de veri?cación ?Checklist?. Sector Strategy and Policy Paper Series. Washigton, D.C.

Inter-American Development Bank . 2002. El desafío de desastres naturales en América Latina y el Caribe: Plan de Acción Sector Strategy and Policy Paper Series. Washigton, D.C.

IPCC TAR WG1. 2001. Houghton, J.T.; Ding, Y.; Griggs, D.J.; Noguer, M.; van der Linden, P.J.; Dai, X.; Maskell, K.; and Johnson, C.A., ed., Climate Change 2001: The Scientific Basis, Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, ISBN 0-521-80767-0

Kim D.W., Byun H.R., Choi K.S. 2009. Evaluation, Modification, and Application of the Effective Drought Index to 200-Year Drought Climatology of Seoul, Korea. Journal of Hydrology , 378, 1-12

Liang X., Lettenmaier D. P., Wood E. F. 1996. One-dimensional Statistical Dynamic Representation of Subgrid Spatial Variability of Precipitation in the Two-Layer Variable Infiltration Capacity Model, J. Geophys. Res., 101(D16) 21,403-21,422.

Liang X., Lettenmaier D. P., Wood E. F., Burges S. J., 1994: A Simple hydrologically Based Model of Land Surface Water and Energy Fluxes for GSMs, J. Geophys. Res., 99(D7), 14,415-14,428.

Lindström G. 1997. A Simple Automatic Calibration Routine for the HBV Model. Nordic Hydrology, Vol. 28, No. 3, pp. 153-168.

Liu Y., Gupta H. V. 2007. Uncertainty in hydrologic modeling: Toward an integrated data assimilation framework, Water Resour. Res., 43, W07401, Lloyd-Hughes B., Saunders M. A. 2002. A drought climatology for Europe. Int. J. Climatol., 22, 1571-1592.

Lo J. C.-F., Yang Z.-L., Pielke R. A. 2008. Assessment of three dynamical climate downscaling methods using the Weather Research and Forecasting (WRF) model, J. Geophys. Res., 113, D09112, doi:10.1029/2007JD009216.

Lorenz E. N., 1969: Atmospheric predictability as revealed by naturally occurring analogs. J. Atmos. Sci., 26, 639?646.

Lyon B., Zubair L., Ralapanawe V., Yahiya Z. 2009. Finescale evaluation of drought in a tropical setting: Case study in sri lanka. Journal of Applied Meteorology and Climatology, 48 (1), 77?88, doi:10.1175/2008JAMC1767.

Madsen H. 2003. Parameter estimation in distributed hydrological catchment modelling using automatic calibration with multiple objectives, Adv. Water Resour., 26, 205?216.

Madsen H., Jacobsen T. 2001. Automatic calibration of the MIKE SHE integrated hydrological modeling system. 4th DHI Software Conference, 6-8 June, 2001, Scanticon Conference Centre, Helsingør, Denmark

Madsen H. 2000. Automatic calibration of a conceptual rainfall-runoff model using multiple objectives. Journal of Hydrology 235, 276-288.

Magaña V. O., Amador J. A., Medina S. 1999. The mid-summer drought over Mexico and Central America, J. Clim., 12, 1577?1588,
doi:10.1175/1520-0442(1999)012¡1577:TMDOMA¿2.0.CO;2.

McEntire D.A. 2007. The importance of Multi and Inter-disciplinary research on disasters and for emergency management. In McEntire, D.A. (ed) Disciplines, Disasters, and Emergency Management. Springfield, IL: Charles C. Thomas, pp. 3-14.

McKee T.B., Doesken N. J., Kliest J. 1993. The relationship of drought frequency and duration to time scales. In Proceedings of the 8th Conference of Applied Climatology, 17-22 January, Anaheim, CA. American Meterological Society, Boston, MA. 179-184.

Méndez M., Magaña V. 2010. Regional Aspects of Prolonged Meteorological Droughts over Mexico and Central America. Journal of Climate 23, 1175-1188.

Mishra A.K., Singh V.P. .2010. A review of drought concepts, Journal of Hydrology, 391:202-216

Monacelli G., Galluccio M.C., Abbafati M. 2005. Drought within the context of the Region VI-WDI, the water and drought index - Tenth Session Of Working Group On Hydrology Regional Association VI (Europe). World Meteorologial Organization. Weather, Climate and Water. Pruhonice, Czech Republic.

Mora S. 1999. Disaster prevention and sustainable development in Central America. In: Slope Stability Engineering; Yagi, Yamagami & Jiang, Eds; Balakema; p. 1247-1252

Mora S., Keipi K. 2006. Disaster risk management in development projects: models and checklists. Bulletin of Engeneering Geology and the Environment, 65, 155-165.

Mishra A., Singh V. 2010. A review of drought concepts, Journal of Hydrology, 391(1-2), 204-216Mora, S. (2009). Disasters are not natural: risk management, a tool for development Geological Society, London, Engineering Geology Special Publications, 22(1), 101-112

Morid S., Smakhtin V., Moghaddasi M., 2006. Comparison of seven meteorological indices for drought monitoring in Iran. Int. J. Climatol., 26, 971-985

Mölders N., Raabe A., 1997. Testing the effect of a two-way coupling of a meteorological and a hydrologic model on the predicted local weather. J. Atmos. Res., 45, 81?107.

Narasimhan B., Srinivasan R. 2005. Development and evaluation of Soil Moisture Deficit Index (SMDI) and Evapotranspiration Deficit Index (ETDI) for agricultural drought monitoring. Agricultural and Forest Meteorology, Vol. 133, pp. 69-88

National Oceanic and Atmospheric Adiministration (NOAA) Glossary. United States Department of Commerce.

Nelder J. A., Mead R. 1965. A simplex method for function minimization. Computer Journal 7, 308-313.

Neumayer E., Plümper T. 2007. The Gendered Nature of Natural Disasters: The Impact of Catastrophic Events on the Gender Gap in Life Expectancy, 1981-2002, Annals of the Association of American Geographers, 97(3), 551-566

Pappenberger F, Beven K., Ratto M., Matgen P. 2008. Multi-method global sensitivity analysis of flood inundation models. Adv Water Resour 31(1)-14

PESA-FAO. 2009. Especial: Guatemala en crisis alimentaria. Extraído de: http://www.pesacentroamerica.org/Guatemala/noticias/especial-guatemala.php

Portig W. H. 1965. Central American rainfall, Geogr. Rev., 55, 68-90

Programa Estado de la Nación. 2011. Informe Estado de la Región en Desarrollo Humano Sostenible. Capítulo 2: Panorama demográfico. Capítulo 3: Equidad e integración social. San José, Programa Estado de la Nación.

Refsgaard J. C. 1997. Parameterisation, calibration and validation of distributed hydrological models, J. Hydrol., 198, 69?97.

Rivera E., Amador J. 2009. Predicción Estacional del Clima en Centroamérica mediante la reducción de escala dinámica. Parte II: Aplicación del modelo MM5v3. Revista de Matemática: Teoría y Aplicaciones. 16(1), 76-104.

Rivera E., Amador J. 2008. Predicción Estacional del Clima en Centroamérica mediante la reducción de escala dinámica. Parte I: Evaluación de los Modelos de Circulación General CCM3.6 y ECHAM4.5. Revista de Matemática: Teoría y Aplicaciones 15(2), 131-173.

Rosenbrock H. 1960. An automatic method for finding the greatest or least value of a function. The Computer Journal 3: 175?184. doi:10.1093/comjnl/3.3.175. ISSN 0010-4620

Seibert J. 2002. HBV light version 2. User s manual, Environmental Assessment, SLU, Uppsala.

Seibert, J. 1997. HBV light version 1.2. User s manual, Uppsala University, Dept. of Earth Sciences, Hydrology, Uppsala

Serrano S.M., Beguería S., López-Moreno J.I. 2010. A multi-scalar drought index sensitive to global warming: the standardized precipitation evapotranspiration index - SPEI. J Clim 23: 1696-1718

Seuffert G., Gross P., Simmer C. 2002: The influence of hydrologic modeling on the predicted local weather: Two-way coupling of a mesoscale weather prediction model and a land surface hydrologic model, Journal of Hydrometeorology, 3, 505-523.

Sorooshian S, Gupta V.K., Fulton J.L. 1983. Evaluation of maximum likelihood parameter estimation techniques for conceptual rainfall-runoff models: Influence of calibration data variability and length on model credibility. Water Resour. Res. 19 (1), pp. 251-259.

Sorooshian S., Duan Q., Gupta V. K. 1993. Calibration of rainfall-runoff models: Application of global optimization to the Sacramento Soil Moisture Accounting Model, Water Resour. Res., 29(4), 1185-1194, doi:10.1029/92WR02617.

Sorooshian S., Dracup J. A. 1980. Stochastic parameter estimation procedures for hydrologic rainfall-runoff models: Correlated and heteroscedastic error cases, Water Resour. Res., 16, 430?442, http://dx.doi.org/10.1029/WR016i002p00430doi:10.1029/WR016i002p00430.

Staubwasser M., Weiss H. 2006. Holocene climate and cultural evolution in late prehistoric?early historic West Asia, Quaternary Research . doi:10.1016/j.yqres.2006.09.001

Stedinger J. R., Vogel R. M., Lee S. U., Batchelder R. 2008. Appraisal of the generalized likelihood uncertainty estimation (GLUE) method, Water Resour. Res., 44, W00B06, doi:10.1029/2008WR006822

Todini E. 1988. Rainfall-runoff modelling - past, present and future. J. Hydrol. 100, 341-352.

The United Nations Office for Disaster Risk Reduction, Terminology, retrieved from http://www.unisdr.org/we/inform/terminology on July, 2008.

Tsakiris G. Loukas A., Pangalou D., Vangelis H., Tigkas D., Rossi G., Cancelliere A. 2004. Chapter 7. Drought Characterization, Drought Management Guidelines Technical Annex, Options Méditerraneennes, Séries B., no. 58, 85-102.

United Nations, 2010. Women and natural disasters. A regional analysis on Asia and the Pacific., Social Development Division. United Nations Economic and Social Commission for Asia and the Pacific. Bangkok.

U.S. Army Corps of Engineers .1998. Water Resources Assessment of El Salvador. U.S. Army Corps of Engineers.

van den Dool H. 1994. Searching for analogs, how long must we wait? Tellus, 46A, 314-324.

van Griensven A., Meixner T., Grunwald S., Bishop T., Diluzio M., Srinivasan R. 2006. A global sensitivity analysis tool for the parameters of multi-variable catchment models. Journal of hydrology, 324 (1-4), 10-23.

Vitart F., Anderson J.L. 2001. Sensitivity of Atlantic Tropical Storm Frequency to ENSO and Interdecadal Variability of SSTs in an Ensemble of AGCM Integrations. American Meteorological Society. 14, 533-545

Wagener T., Gupta, H. V. 2005. Model identification for hydrological forecasting under uncertainty, Stoch. Environ. Res. Ris. Assess., 19, 378-387

Wagener T., Wheater H.S., Gupta H.V. 2004. Rainfall-Runoff Modellin in Gauged and Ungauged Catchments. Imperial College Press. London. pp. 2,41.

Ward R.C., Robinson M. 2000. Principles of Hydrology, 4th edn., McGraw-Hill, London. pp. 270-278

Waring S.C., Brown B.J. The threat of communicable diseases following natural disasters: a public health response. 2005. Disaster Management Response. 3(2): 41-7.

Waylen, P., Laporte S. M. 1999. Flooding and the El Niño-Southern Oscillation phenomenon along the Pacific coast of Costa Rica. Hydrol. Process., 13: 2623?2638. doi: 10.1002/(SICI)1099-1085(199911)13:16¡2623::AID-HYP941¿3.0.CO;2-H

Waylen P.R., Caviedes C.N., Quesada M.B. 1996. Interannual variability of monthly precipitation in Costa Rica. Journal of Climate. 9, 2606-2613.

Weiss H. 2000. Beyond the Younger Dryas: Collapse as Adaptation to Abrupt Climate Change in Ancient West Asia and the Eastern Mediterranean. In: Bawden, G., Reycraft, R. (Eds.), Confronting Natural Disaster: Engaging the Past to Understand the Future. University of New Mexico Press, Albuquerque, 2000, pp. 75?98.

Westerberg I. K. 2011. Observational Uncertainties in Water-Resources Modelling in Central America: Methods for Uncertainty Estimation and Model Evaluation (PhD thesis). Uppsala University.

Westerberg I. K., Guerrero J-L., Younger P-M., Beven, K. J. Seibert, J., Halldin S., J-E. Freer, Xu C-Y. 2010. Calibration of hydrologic models using flow-duration curves. Hydrol. Earth Syst. Sci. Discuss., 7:9467-9522.

Wetterhall F. 2005. Statistical downscaling of precipitation from large-scale atmospheric circulation. Comparison of methods and climate regions. PhD thesis, Uppsala University

Wilby R.L., Wigley T.M.L. 1997. Downscaling general circulation model output: a review of methods and limitations. Progress in Physical Geography, Vol. 21, No. 4, 530-548.

Wilhite D.A. and Glantz, M.H. 1985. Understanding the drought phenomenon: The role of definitions. Water International 10: 111?20.

Wilks D. 1995. Statistical methods in the atmospheric sciences. Cambridge University Press,San Diego, California, USA, 465 pp

Wood, A. W., L. R. Leung, V. Sridhar, and D. P. Lettenmaier, 2004. Hydrologic implications of dynamical and statistical approaches to downscaling climate model outputs. Climatic Change, 62: 189-216.

Wood, A. W., Maurer, E. P., Kumar, A., and Lettenmaier, D. P. 2002, Long Range Experimental Hydrologic Forecasting for the Eastern U.S.?, J. Geophys. Res. 107 (D20), 4429.

World Meteorological Organization, Drought Monitoring and Early Warning: Concepts, Progress and Future Challenges, WMO Report No. 1006, ISBN 92-63-11006-9, 2006.

WMO-UNESCO. 1992. International Glossary of Hydrology. 2nd Edition. WMO Report No. 385.

Xu C. WASMOD-The water and snow balance modeling system. In: Singh V.P., Frevert D.K. Mathematical models of small watershed hydrology and applications. Chapter 7.

Xu Z., Yang Z-L. 2012: An Improved Dynamical Downscaling Method with GCM Bias Corrections and Its Validation with 30 Years of Climate Simulations. J. Climate, 25, 6271?6286

Yang Shao-E; Wu Bing-fang. 2010. Calculation of monthly precipitation anomaly percentage using web-serviced remote sensing data, Advanced Computer Control (ICACC), 2010 2nd International Conference on , vol.5, no., pp.621-625, 27-29 March 2010
doi: 10.1109/ICACC.2010.5486796

Yapo P, Gupta H.V. and Sorooshian S. 1996. Automatic Calibration of Conceptual Rainfall-Runoff Models: Sensitivity to Calibration Data, Journal of Hydrology, 181(1-4), pp. 23-48

Yang J., P. Reichert, and K. C. Abbaspour. 2007a Bayesian uncertainty analysis in distributed hydrologic modeling: A case study in the Thur River basin (Switzerland), Water Resour. Res., 43, W10401, doi:10.1029/2006WR005497.

Yang J., Reichert P., Abbaspour K. C., Yang h. 2007b. Hydrological modelling of the Chaohe Basin in China: Statistical model formulation and Bayesian inference, J. Hydrol., 340, 167?182, doi:10.1016/j.jhydrol.2007.04.006.

Zorita E., von Storch H. 1999. The analogue method as a simple statistical downscaling technique: Comparison with more complicated methods. Journal of Climate 12, 2474?2489.

Zorita E., Hughes J.P., Lettenmaier D.P., von Storch H., 1995. Stochastic characterization of regional circulation patterns for climate model diagnosis and estimation of local precipitation.Journal of Climate 13, 223?234.