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Hydro-Climatic Variability and Change in Central America

Supporting Risk Reduction Through Improved Analyses and Data

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Abstract

Quesada-Montano, B. 2017. Hydro-Climatic Variability and Change in Central America. Supporting Risk Reduction Through Improved Analyses and Data. (Variabilitet och förändring av hydrologi och klimat i Mellanamerika. Stöd för riskreducering genom förbättrade analyser och data). *Digital Comprehensive Summaries of Uppsala Dissertations from the Faculty of Science and Technology* 1570. 70 pp. Uppsala: Acta Universitatis Upsaliensis. ISBN 978-91-513-0092-4.

Floods and droughts are frequent in Central America and cause large social, economic and environmental impacts. A crucial step in disaster risk reduction is to have a good understanding of the causing mechanisms of extreme events and their spatio-temporal characteristics. For this, a key aspect is access to a dense network of long and good-quality hydro-meteorological data. Unfortunately, such ideal data are sparse or non-existent in Central America. In addition, the existing methods for hydro-climatic studies need to be revised and/or improved to find the most suitable for the region's climate, geography and hydro-climatic data situation. This work has the ultimate goal to support the reduction of risks associated with hydro-climatic-induced disasters in Central America. This was sought by developing ways to reduce data-related uncertainties and by improving the available methods to study and understand hydro-climatic variability processes. In terms of data-uncertainty reduction, this thesis includes the development of a high resolution air temperature dataset and a methodology to reduce uncertainties in a hydrological model at ungauged basins. The dataset was able to capture the spatial patterns with a detail not available with existing datasets. The methodology significantly reduced uncertainties in an assumed-to-be ungauged catchment. In terms of methodological improvements, this thesis includes an assessment of the most suitable combination of (available) meteorological datasets and drought indices to characterise droughts in Central America. In addition, a methodology was developed to analyse drought propagation in a tropical catchment, in an automated, objective way. Results from the assessment and the drought propagation analysis contributed with improving the understanding of drought patterns and generating processes in the region. Finally, a methodology was proposed for assessing changes in both hydrological extremes in a consistent way. This contrasts with most commonly used frameworks that study each extreme individually. The method provides important characteristics (frequency, duration and magnitude), information that can be useful for decisions within risk reduction and water management. The results presented in this thesis are a contribution, in terms of hydro-climatic data and assessment methods, for supporting risk reduction of disasters related with hydro-climatic extremes in Central America.

Keywords: Central America, climate variability, disaster risk reduction, droughts, drought indices, floods, hydrological model, process constraints, statistical downscaling, uncertainty, ungauged basins, water resources.

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Akademisk avhandling som för avläggande av filosofie doktorsexamen i hydrologi vid Uppsala universitet kommer att offentligen försvaras i Axel Hambergsalen, Geocentrum, Villavägen 16, Uppsala, fredagen den 24 november 2017, klockan 10:00. Professor Denis Hughes, Rhodes University, Sydafrika är fakultetsopponent. Disputationen sker på engelska.

Referat

Quesada Montano, B., Variabilitet och förändring av hydrologi och klimat i Mellanamerika. Stöd för riskreducering genom förbättrade analyser och data. Acta Universitatis Upsaliensis. *Digital Comprehensive Summaries of Uppsala Dissertations from the Faculty of Science and Technology* 1570. 70 sid. Uppsala ISBN 978-91-513-0092-4

Översvämningar och torka inträffar ofta i Mellanamerika och orsakar stora skador på samhälle, ekonomi och miljö. En kritisk del av riskreduceringen är förståelsen av mekanismerna bakom extremhändelserna, och deras rumsliga och tidskarakteristik. En nyckelfaktor är tillgång till långa tidsserier av rumsligt täckande hydrometeorologiska data av bra kvalitet. I Mellanamerika är sådana ideala data tyvärr sällsynta eller saknas helt. Dessutom behöver befintliga metoder för hydro-klimatisk analys revideras och/eller förbättras för att identifiera de mest lämpade metoderna för regionens klimat, geografi och situationen vad gäller hydrologiska och meteorologiska data. Det övergripande syftet med denna avhandling har varit att stödja arbetet med riskreducering i Mellanamerika vid hydrologiska extremhändelser som sätts igång av extrema väderhändelser. För att bidra till detta utvecklades metoder för att minska datarelaterade osäkerheter och för att förbättra tillgängliga metoder för att studera och förstå de processer som ligger bakom variabiliteten i hydrologi och klimat. Dataosäkerheten minskades genom utveckling av ett nytt dataset för lufttemperatur med hög rumslig upplösning och en metodik för att begränsa osäkerheten i modellberäknad vattenföring i ett område där det saknas observationer. Det nya datasetet kunde fånga rumsliga mönster på en detaljnivå som hittills inte varit möjlig. Metodiken möjliggjorde en klar minskning i osäkerheten hos vattenföringen i ett avrinningsområde som behandlades som om det saknade data. Avhandlingen innehåller också en metodik för att fastlägga den mest lämpade kombinationen av tillgängliga klimatdataset och torkindex för att karakterisera torka i Mellanamerika. Därutöver utvecklades en metod för att studera torkans fortplantning i ett tropiskt avrinningsområde på ett objektivt och automatiserat sätt. Slutligen föreslås en metod för att hantera förändringar av både översvämning och torka på ett konsistent sätt som förenklar användningen av resultaten för en beslutsfattare. Dessa metoder bedömdes användbara för att förbättra karakteriseringen och förståelsen av extrema hydrologiska händelser i Mellanamerika. Resultaten i denna avhandling ger bidrag till förståelsen av hydrologiska och klimatextremer genom förbättrade data och analysmetoder som i förlängningen kommer att stödja riskreduceringsarbetet i Mellanamerika.

Nyckelord: avrinningsområden utan vattenföringsdata, hydrologisk modell, klimatvariabilitet, katastrofriskreducering, Mellanamerika, osäkerhet, processbegränsningar, statistisk nedskalning, torka, torkindex, vattenresurser, översvämning.

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Defensa presentada en la Universidad de Uppsala evaluada públicamente en el salón Axel Hamberg, en el Departamento de Ciencias de la Tierra, Villavägen 16, Uppsala, viernes, 24 de noviembre del 2017 a las 10:00 para el grado académico de Doctor de Filosofía. Oponente académico: Profesor Denis Hughes de la Universidad de Rhodes, Sufáfrica. La defensa se llevará a cabo en inglés.

Resúmen
Quesada Montano, B., Variabilidad y cambio hidro-climático en Centroamérica. Apoyando la reducción del riesgo por medio de la mejora de métodos de análisis y datos.. Acta Universitatis Upsaliensis. *Digital Comprehensive Summaries of Uppsala Dissertations from the Faculty of Science and Technology* 1570. 70 pp. Uppsala ISBN 978-91-513-0092-4

Las sequías e inundaciones son frecuentes en Centroamérica y causan grandes problemas sociales, económicos y ambientales. Un aspecto crucial en la reducción del riesgo consiste en entender los mecanismos que causan dichos eventos, y sus características espacio-temporales. Para lograr esto es necesario tener acceso a una red de datos hidro-meterológicos densa, con series largas, y de buena calidad. Desafortunadamente, este no es el caso en Centroamérica. Además, los métodos para hacer estudios hidro-climáticos requieren ser evaluados y/o mejorados para asegurar su aplicabilidad en la región (su clima, su geografía y los datos disponibles). Este trabajo tiene como meta apoyar la reducción del riesgo de desastres asociados a eventos hidro-meteorológicos extremos en Centroamérica. Esto se consigue a partir de la reducción de incertidumbres asociadas a los datos, y de la mejora de métodos para el estudio de la variabilidad hidro-climática. Para reducir la incertidumbre de los datos, este trabajo incluye el desarrollo de una base de datos de temperatura de alta resolución y el desarrollo de una metodología para reducir las incertidumbres en datos simulados de caudal. Con la nueva base de datos se logra reconocer patrones espaciales a un nivel de detalle no antes captado por otras bases de datos. Por otro lado, la metodología redujo significativamente las incertidumbres de los datos simulados de caudal. En cuanto a métodos, esta tesis incluye una evaluación para encontrar la mejor combinación de índices de sequía y base de datos para la caracterización de sequías en la región. Además, se desarrolló una metodología para analizar la propagación de la sequía en una cuenca tropical, de una manera objetiva y automatizada. Los resultados de estos dos pasos ayudaron a mejorar la comprensión de los patrones y los mecanismos de generación de las sequías. Finalmente, se incluyó un método para evaluar los cambios en los patrones de sequías e inundaciones de una manera consistente, y no de manera individual como usualmente se ha hecho. Así fue posible obtener la frecuencia, duración y magnitud en ambos extremos hidrológicos. Esta información podría constituir una herramienta útil para el manejo del riesgo y del recurso hídrico.

Keywords: Centroamérica, variabilidad climática, reducción del riesgo de desastres, sequías, inundaciones, índices de sequía, modelos hidrológicos, reducción de escala estadística, incertidumbres, cuencas no aforadas, recurso hídrico.

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List of Papers

This thesis is based on the following papers, which are referred to in the text by their Roman numerals.

I Hidalgo HG, Alfaro EJ, **Quesada-Montano B.** 2017. Observed (1970-1999) climate variability in Central America using a high-resolution meteorological dataset with implication to climate change studies. Climatic Change 141 (1): 13–28 DOI: 10.1007/s10584-016-1786-y

II **Quesada-Montano, B.,** Westerberg, I.K., Fuentes-Andino, D., Hidalgo, H., Halldin, S. 2016. Can climate variability information constrain a hydrological model for an ungauged Costa Rican catchment? In review, after revision. Hydrological Processes.

III **Quesada Montano, B.**, Westerberg, I. K., Hidalgo, H., Wetterhall, F., Halldin, S. 2016. Characterising droughts in Central America with uncertain hydro-meteorological data. In review. Journal of Theoretical and Applied Climatology.

IV **Quesada-Montano, B.**, Birkel, Ch., Van Loon, A., Wetterhall, F., Hidalgo, H., Westerberg, I.K., 2017. Automation for estimation of drought propagation characteristics in a tropical catchment. Manuscript.

V **Quesada-Montano, B.**, Di Baldassarre, G., Rangecroft, S., van Loon, A. 2017. Hydrological change: a consistent assessment of hydrological extremes. In review, after revision. Advances in Water Resources.

In Paper **I**, I contributed to the writing of the codes to develop the temperature dataset, part of the analysis and the writing of the paper. In Paper **II,** I contributed to the definition of the study (together with Ida W. and Sven H.), writing the paper, the modelling, the development and application of the constraints, and the analysis in terms of efficiency measures and hydrological signatures. In Paper **III**, I contributed to the definition of the study (together with Fredrik W., Ida W., Sven H. and Hugo H.), was responsible for gathering and assessing the meteorological data (with Fredrik W.), the calculation of the indices, the comparison of the combinations of meteorological drought indices and datasets, and the writing of the paper. In Paper **IV**, I was responsible for defining the study, the writing, the development of the algorithm for automation of drought propagation, and the drought propagation analysis (together with Anne VL.). In Paper **V**, the definition of the study, the development of the methodology and the writing of the paper were done together with Giuliano DB. I contributed to the application example and its analysis. Discussions and feedback with co-authors: Sven H., Hugo H., Ida K., Fredrik W., Giuliano DB., Anne VL., Eric A., Diana F. and Sally R., helped further develop the ideas and writing in all the papers

In addition I have contributed to the following papers during my PhD studies in Uppsala University:

> Juston, J. M., Kauffeldt, A., **Montano, B. Q.**, Seibert, J., Beven, K. J. and Westerberg, I. K. 2013. Smiling in the rain: Seven reasons to be positive about uncertainty in hydrological modelling. Hydrological Processes, 27: 1117–1122. doi: 10.1002/hyp.9625
>
> Hidalgo, H. G., Amador, J. A., Alfaro, E. J., and **Quesada, B**. 2013. Hydrological Climate Change Projections for Central America, Journal of Hydrology, 495:94-112. doi:10.1016/j.jhydrol.2013.05.004

Contents

Abbreviations

AMO	Atlantic Multidecadal Oscillation
CAMS	Climate Anomaly Monitoring System
CHIRPS	Climate Hazards Group InfraRed Precipitation with Station data
CLLJ	Caribbean Low-Level Jet
CR	Classical Rainfall deficit drought
DRR	Disaster Risk Reduction
EDI	Effective precipitation index
ENSO	El Niño Southern Oscillation
GA	Genetic Optimisation Algorithm
GCM	Global Climate Model
GDP	Gross Domestic Product
GRDC	Global Runoff Database Centre
ICE	Instuto Costarricense de Electricidad de Costa Rica
IMN	Instituto Meteorológico Nacional de Costa Rica
ITCZ	Intertropical Convergence Zone
PDO	Pacific Decadal Oscillation
PET	Potential Evapotranspiration
POT	Peaks Over Threshold
P_{ss}	Peirce Skill Score
PUB	Predictions in Ungauged Basins
SST	Sea surface temperature
SPEI	Standardised Precipitation and Evapotranspiration index
SPI	Standardised Precipitation Index
SSI	Standardised streamflow index
T_{avg}	Average surface temperature
TNA	Tropical North Atlantic index

Introduction

A large part of the world's population is exposed to the occurrence of extreme hydro-climatic events – floods and droughts – associated to climate variability (Dilley *et al.*, 2005). The regions exposed to floods and droughts concentrate high gross domestic product (GDP) and agricultural value, and many of these regions are located in developing countries (Dilley *et al.*, 2005). Central America is considered a hotspot for the occurrence of floods and droughts (Aguilar *et al.*, 2005; Dilley *et al.*, 2005; Brenes, 2010; Pérez-Briceño *et al.*, 2016). Poor socio-economic conditions and lack of planning hinders the ability of the regional governments to cope with the negative consequences of these hazards, thus it is frequent that disasters follow such events (PEN, 2011; Estado de la Nación, 2016). Floods and droughts cause large social and environmental impacts and are responsible for significant losses in the agriculture, hydropower, infrastructure and tourism sectors, which are key for the economic development of the region (Brenes, 2010; Baez *et al.*, 2017). Hydro-climatic related disasters pose one of the greatest threats to livelihoods in the region (Dilley *et al.*, 2005), even though the efforts to reduce the risks of these types of disasters have significantly increased in the region since the 1990's (Programa Estado de la Nación, 2016). This reveals that there is still much improvement to be made in terms of disaster risk reduction (DRR) and management. A crucial step in achieving this, is to have a good understanding of the causing mechanisms of extreme events and their spatio-temporal characteristics, and to improve the ability to predict them. It is therefore necessary to understand the natural variability of climate and water resources. This includes understanding under which circumstances and how often extreme hydro-climatic events occur, and identify any changing patterns in such extremes, so that better decisions can be taken and risks associated with such events can be reduced.

A key aspect in the study of variability of climate and water resources is access to good-quality hydro-meteorological data. Ideally, one should have 1) a gauging network sufficiently dense and distributed so that the high hydro-climatic spatial variability is well captured, 2) a long-time coverage with no missing data so that the temporal variability is captured and information about extreme events is included, 3) measurements made with good equipment and techniques to ensure the quality of the data, and 4) well-managed data easily available so that they can be used for research, risk management and planning. Unfortunately, such ideal data are sparse or non-existent in Central America, where the hydro-meteorological observation network is scant and has quality problems (Portig, 1965; Aguilar *et al.*, 2005; Westerberg *et al.*, 2014). Precipitation data are the most accessible data type in the region, but studies done at the local scale point to substantial quality problems (Westerberg *et al.*, 2010). Variables such as potential evapotranspiration, radiation, soil moisture and groundwater levels are seldom measured. Several regional and global meteorological datasets have been derived from combining different data products, such as ground observations, satellite images and atmospheric model simulations. These products are commonly interpolated to a grid-cell format, but often with a spatial resolution too coarse to capture the spatial heterogeneity of the climate of Central America.

Hydrological data are more difficult to obtain than meteorological data given that many catchments in the region are ungauged, and often, for those that are gauged, data are owned by private parties and often not accessible. Hydrological data can be inferred from hydrological models. The traditional modelling approach focuses on identifying the parameter sets for which the observed hydrograph is best represented. This requires good quality discharge data, which makes this approach inadequate for application in ungauged basins (Hrachowitz *et al.*, 2013).

Another important aspect in the study of variability of climate and water resources is the methodology used. The method should respond to the needs, and the climate and geography of the region, in relation to the available data.

Aim of the thesis

The ultimate goal of this thesis is to support the reduction of risks associated with hydro-climatic-induced disasters in Central America. This is sought by developing ways to reduce data-related uncertainties, which prevent the study of hydro-climatic variability and change, and by improving the available methods to study and understand hydro-climatic variability. The specific objectives through the five papers forming this thesis, are described in Table 1.

Table 1. *Objectives of this thesis reached by the different papers.*

Study	Develop data and methods to reduce the uncertainties that limit hydro-climatic variability and change studies in Central America.	Improve process understanding of hydro-climatic variability and change.	Improve data and methods for assessment of hydro-climatic extremes.
Paper **I**	X	X	
Paper **II**	X	X	
Paper **III**			X
Paper **IV**		X	X
Paper **V**			X

Floods and droughts

Disasters associated to hydro-climatic extremes in Central America

Central America is highly vulnerable to the effects of extreme hydro-climatic events associated to climate variability. During the last decades disasters of this type have shown a significant increasing trend and this has caused many problems in the region (Programa Estado de la Nación, 2016). These problems are largely attributed to the strong dependency that many economic activities have on the seasonal variations of climate and water resources. Thus, disruptions of such variations often bring large consequences (Rivera and Amador, 2008). This situation is worrying because the region not only has problems with reducing risks under the current conditions, but the situation might worsen in the future as climate predictions indicate (IPCC, 2007; Paper **I**).

Droughts in Central America are often related to inter-annual variations of precipitation - i.e. temporal distribution and accumulated total amounts (Waylen *et al.*, 1996b; Alfaro *et al.*, 1998). These variations have been related to different climate phenomena through teleconnection mechanisms (see section Study Area), including the Sea Surface Temperatures (SSTs) of the surrounding oceans and the Caribbean Low Level Jet or CLLJ (Hidalgo *et al.*, 2015).

Many economic activities in the region are vulnerable to the occurrence of droughts in the region. Agriculture for example, has a high socio-economic importance, since it represents a significant component of GDP and is one of the main sources of employment, especially in rural areas (Echeverria, 2016). A large part of the agriculture is rain-fed, which makes it highly vulnerable to changes in the precipitation regime. Hydro-power production is an important source of electricity and is also an important economic input, and the production can be affected under drought conditions (Echeverria, 2016). Other sectors such as drinking water, tourism, and fishing are also affected by droughts (Brenes, 2010). In addition, large problems with malnutrition have been reported during severe drought events, such as those occurring in 2000–2001 (ECLAC, 2002; Wolf *et al.*, 2007), 2009 (Chen *et al.*, 2016) and 2014 (CNE, 2015). With all the problems that droughts cause in the region, good knowledge about droughts is needed, yet, even basic studies that provide the spatio-temporal characteristics are scarce. Similarly, there is limited knowledge about the different drought propagation processes in Central

America and in the tropics in general (Paper **IV**). Thus, the quantification and understanding of drought characteristics and processes would benefit water and disaster risk management.

Similarly, extremely high rainfall and hydrological events are frequent in Central America, and are the result of climate variability. Like droughts, the occurrence of these events is influenced by the SSTs anomalies of the surrounding oceans and other large scale modulators of climate such as the Atlantic Multidecadal Oscillation (AMO) (Enfield and Alfaro, 1999; Waylen and Laporte, 1999; Maldonado *et al.*, 2013). At shorter time scales, these can be the result of the influence of tropical storms (including hurricanes), easterly waves, cold air mass intrusions (Pérez-Briceño *et al.*, 2016). In addition, extreme events can be caused by the so called, 'temporales', which are relatively short periods of continued rainfall (from one to four days), related to the Intertropical Convergence Zone (ITCZ), cold air mass intrusions, and direct and indirect effect of hurricanes (Fernandez, 1996). Extreme rain events cause serious problems such as flooding leading to damages in infrastructure, landslides and loss of lives. For example, for the period 2010–2013, 10.785 houses were totally destroyed due to extreme rainfall events and flooding in Costa Rica, El Salvador, Guatemala and Panama (Programa Estado de la Nación, 2016).

Flood and drought concepts

Floods and droughts are referred to as opposite extremes, but this is usually not reflected in the methods used for their study in the research literature. For defining floods, usually shorter time scales (e.g. daily) and more extreme exceedance percentiles (e.g. 1^{st}) are used than for defining droughts, (e.g. 80^{th} exceedance percentiles at monthly scale). This stems, to a great extent, from the differences in the impacts of each extreme. For floods, the impacts can be visible relatively fast, in a matter of hours or weeks (Van Loon *et al.*, 2016a). For droughts, impacts can take longer until these are visible, in the order of months or years, or in cases even pass unnoticed as these accumulate over a period of time (Mishra and Singh, 2010; Van Loon *et al.*, 2016a). Added to that, the impacts of droughts are non-structural (Mishra and Singh, 2010), while infrastructure damages are much more common with floods. Also, since drought impacts a diversity of sectors (in response to the wide range of water demands), the impacts may affect sectors beyond those directly affected (Mishra and Singh, 2010).

As a result of the complexity of drought impacts, there are several definitions of drought. Some definitions respond to the socio-economic sector that suffers the impact, e.g. agricultural and socio-economic drought (Dracup *et al.*, 1980; Wilhite and Glantz, 1985; Mishra and Singh, 2010). Droughts can be subdivided in terms of the different components of the hydrological cycle, including precipitation, soil moisture and groundwater discharge. In this thesis droughts are defined as the state of deviation from normal of any of the components of the hydrological cycle. In this way, if the variable in question is exceptionally below normal, it is considered a drought (Van Loon *et al.*, 2016a). In addition, in this thesis, commonly used sub-divisions of droughts are used to differentiate between deficits in the different components of the hydrological cycle. Precipitation deficits are referred to as meteorological drought, and deficits in river and groundwater discharge are referred to as hydrological drought. From these, the ones for which most of the impacts are reported are for hydrological droughts, given the dependence of the society and the ecosystem on catchment stores (Van Loon, 2015).

In this work, extreme rain events were defined in terms of anomalies of total annual precipitation. Floods were defined as when daily or monthly discharge was above a predefined threshold.

Drought propagation

The way in which drought propagates from meteorological drought to soil moisture drought to hydrological drought is called drought propagation (Eltahir and Yeh, 1999). The usual drought propagation pattern is that droughts become fewer (pooling), longer and delayed as they propagate from droughts in precipitation, to soil moisture, river and groundwater discharge (Van Loon, 2015). If there is sufficient storage in the catchment when a severe meteorological drought occurs, the event may result in a relatively less severe river and groundwater discharge drought (i.e. the event is attenuated) (Peters and van Lanen, 2005). How much lag, lengthening pooling and attenuation occurs is determined by climate and catchment characteristics (Peters *et al.*, 2003; Van Lanen *et al.*, 2013; Van Loon and Laaha, 2015). Understanding the cause of hydrological droughts is difficult because many variables interplay to result in hydrological droughts: antecedent precipitation, soil moisture, evapotranspiration and storage.

Some studies have analysed the role of climate and catchment characteristics on hydrological drought development. Van Lanen *et al.*, (2013) used a hydrological model and defined different soil-moisture retention characteristics and groundwater responses, and ran the model at the global scale to cover all Köppen-Geiger climate types. They found that the number of droughts in equatorial and temperate climates are almost twice as many than those in arid and polar climates. They also found that hydrological drought characteristics are controlled by groundwater in climates with high recharge (tropical, temperate and continental climates) and that soil type did not play a major role in either climate type. Additionally, they found that a higher number of hydrological droughts occur for fast-responding systems than for slow-responding ones. On the other hand, Haslinger *et al.* (2014)

found that in small to medium-sized humid catchments hydrological droughts are climate-dominated, though unlike most of the studies on drought propagation, their conclusions were drawn with the use of meteorological drought indices. Van Loon *et al.* (2014) focused on exploring the effect of the different climate types on drought propagation and found that the relationship between duration and volume deficit is not linear (drought deficit has a larger increase as the duration becomes longer), especially when the climate is more seasonal. Thus, the most pronounced hydrological drought events can occur in seasonal types of climates, e.g. monsoonal, semi-arid and boreal climates.

Van Loon and Laaha (2015) studied the role of climate and catchment characteristics in a set of 44 Austrian catchments using observed data. They found that the base flow index, which represents a combination of geology, land use and area characteristics, is highly correlated with drought length. They also found that drought deficit is related to catchment storage and that the effect of climate is related to the duration of dry spells.

In Central America, a study by Birkel (2006) made in 17 catchments in Costa Rica using observed data found longer river discharge droughts with smaller deficit values during the dry season than in the wet season.

From these studies it could be expected that for catchments located in tropical climates the number of hydrological droughts taking place are relatively high, especially for fast-responding systems. Also, that severe events (in terms of duration and deficit volume) can take place, especially in catchments with important groundwater contribution. However, these statements have to be validated in Central America. In addition, there are still many aspects that need to be understood in drought propagation in the tropics, including: what is the role of climate and catchment characteristics in the region? Which processes cause the most severe hydrological drought events?

Hydrological drought types

Based on the generating and propagation processes, Van Loon and Van Lanen (2012) developed a hydrological drought typology. They identified six types: *rain-to-snow season drought*, *cold snow season drought*, *warm snow season drought*, *classical rainfall drought*, *wet-to-dry season drought* and *composite drought*. Because of its tropical climate, in Central America it is only possible to find the three last types.

A classical rainfall drought (CR), as described by its name, is caused by a sustained period with less rainfall than normal. Wet-to-dry season droughts are caused by rainfall deficits during the wet season that result in insufficiently replenished soil moisture and groundwater, which causes a hydrological drought that continues into the dry season. Composite droughts are a result of a combination of different generating mechanisms. In a tropical climate, a composite drought can be formed by a wet-to-dry season drought that combines with one or more classical rainfall droughts and continues into the wet season.

Until now, hydrological drought typology has mostly been applied manually, which can be time consuming when dealing with a long series or with many catchments, and can introduce subjectivity aspects that affect comparability between catchments.

Methods for drought and flood assessment

Drought assessment

A common tool used to quantify drought characteristics are drought indices. Many drought indices have been developed, and a large part of these are based on precipitation. The *standardised precipitation index* (SPI, Mckee *et al.*, 1993) is a widely used method and was recognised by the World Meteorological Organisation for drought characterisation around the world. The index 1) is fairly simple to calculate, 2) is possible to calculate at different accumulation time scales to use as a proxy for soil moisture and hydrological droughts, and 3) is based on precipitation data that are more easily accessible than other variables (e.g. river discharge). Other precipitation-based indices include the *deciles index* (Gibbs and Maher, 1967) and the *effective drought index* (EDI, Byun and Wilhite, 1999). Beguería and Vicente-Serrano (2013) developed a version of the SPI to account for the effects of temperature on drought development and called it the standardised evapotranspiration index (SPEI). Standardised indices have also been calculated in soil moisture (e.g. Sheffield, 2004) and streamflow (e.g. Lorenzo-Lacruz *et al.*, 2013). Although standardised indices are a good alternative for drought assessment, they have some disadvantages. To calculate the index the data of the variable in question need usually to be fitted to a theoretical distribution. This requires long time series and in addition, finding a suitable distribution can be difficult (Stagge *et al.*, 2015). Additionally, SPI and other indices cannot provide important information such as deficit volume, which can be useful in water management. In the lack of soil moisture and hydrological observations, meteorological drought indices (accumulated at several months) have been used to assess soil moisture and hydrological droughts (e.g. in Nalbantis and Tsakiris, 2009; Zhai *et al.*, 2010; Xuchun *et al.*, 2016). However, this is getting increasingly criticised by the research community because of the recent improved understanding of the complexity of drought propagation processes (Hu and Willson, 2000; Teuling *et al.*, 2013; Haslinger *et al.*, 2014).

The threshold-level method, which is based on the theory of runs (Yevjevich, 1967), has become a widely used tool in the study of drought.

With this method a drought is defined when the variable in question is below a previously-defined value or threshold. The method is widely used because data do not have to be fitted to any distribution, and it provides characteristics of timing, length and deficit volume. The duration of the drought event is defined as the consecutive number of days or months (depending on the accumulation time) that the flow is below the threshold. The deficit volume for each drought event is calculated as the sum of the deviations from the threshold.

The reliability of the information that the aforementioned methods can provide is affected by the quality of the data that are used for their calculation (Paper **III**). In addition, there is no best index that suits all regions and/or applications (Smakhtin and Hughes, 2004) and thus, the applicability of a particular index has to be evaluated in each situation.

Drought and flood trend assessment

All the methods described for drought assessment can also be used for detecting changes in drought characteristics through time. In addition, the annual minimum discharge series (similar approach to the annual maximum discharge series) has been used for this purpose (e.g. Renard *et al.*, 2008; Montanari, 2012).

In flood trend assessment a commonly used method is annual maxima series, which contains the annual daily maximum discharge value for each year. Since this method only uses information of one flood per year, it might leave out information from other significant flood events (Lang *et al.*, 1999). Another widely used method is the peaks-over-threshold method (POT), which retains all peak values that 'exceed' a previously defined threshold, instead of only one value per year. Thus, with this method it is possible to control the number of flood occurrences (through selection of the threshold) and to have a wider description of flood generating processes. However, it also has limitations related with the selection of threshold and criteria to retain flood peaks (Lang *et al.*, 1999). Neither of these methods is able to provide frequency, duration and surplus volume at the same time.

The spatial and temporal distributions of the frequency and magnitude of floods and droughts are changing in different parts of the world (Burn and Hag Elnur, 2002; Di Baldassarre *et al.*, 2010; Winsemius *et al.*, 2016; UN-ISDR, 2017). Some of these changes have been attributed to shifts in meteorological variables (e.g. Zhai *et al.*, 2005; Alexander *et al.*, 2006). Other studies have attributed changes in hydrological extremes to the increase in human activities, such as the building of dams, levees, reservoirs and water abstraction (Kottegoda and Natale, 1994; Di Baldassarre *et al.*, 2009; Heine and Pinter, 2012; Blöschl *et al.*, 2013; Rangecroft *et al.*, 2016) The methods usually used for detecting these changes only provide limited information for use in decision making within water and disaster management (Paper **V**). This happens because of two main reasons. First, the floods and droughts are usually studied individually (while in reality, water management considers both extremes). This results in rather different methods used for each extreme, which makes the results hard to compare. Second, the assessment is made based on characteristics such as frequency and/or the absolute value of the flow at a certain moment in time, while other important characteristics such as duration and deficit or surplus volumes are not provided. There is, therefore, a need for a consistent methodology that allows assessing both extremes in an integrated way.

Hydrological modelling in data-scarce regions

Use of additional information to reduce uncertainties in ungauged basins

Hydrological models can be used to simulate long-term discharge data in regions like Central America, where hydrological observations are limited and have quality problems. Common parameter-fitting approaches in hydrological modelling require abundant and good quality data in order to obtain accurate results, and are therefore inadequate for obtaining accurate results for poorly gauged or ungauged basins (Hrachowitz *et al.*, 2013). During the last decades the hydrological community, aware of this issue, recognised the value of different types of information on the hydrological function of a catchment for model calibration and regionalisation. During the International Association of Hydrological Sciences Decade through its initiative, 'prediction in ungauged basins' (PUB), the main focus was to reduce uncertainties in hydrological predictions in ungauged basins based on this new philosophy (Wagener and Montanari, 2011). The philosophy attempts to improve understanding of the underlying catchment processes, and have the hydrological models represent that improved understanding (Hrachowitz *et al.*, 2013). Improved model representation of catchment processes has focused on extracting the most possible information from the available data and using it in the modelling process (Hrachowitz *et al.*, 2013). Such information is commonly referred to in the literature as additional information and can appear both as hard quantifiable data and as soft data. Additional types of information in the form of hard data can come in the form of hydrological signatures that are used to capture the dominant processes and spatiotemporal characteristics of the rainfall-runoff response (Westerberg and McMillan, 2015). Commonly, signatures describe the flow regime (e.g. shape of the recession curve and slope of the flow duration curve), and the water balance (e.g. monthly water balance and runoff coefficient). Another example of hard data information is the use of measurements of physical attributes of the catchment to quantify soil moisture accounting, runoff, recharge and infiltration parameters, as done by Kapangaziwiri and Hughes (2008). An example of additional soft data information is the use of expert knowledge. For example, Seibert and McDonnell (2002) excluded system representations that disagreed with expert perception of reality. Expert knowledge has also been used to exclude parameter relationships that result in model representations that are inconsistent with the modeller's understanding of the system in what is referred to as *parameter constraints* (e.g. Gharari *et al.*, 2014a, 2014b; Hrachowitz *et al.*, 2014; Smith *et al.*, 2016). Additional information about catchment processes (e.g. water balance partitioning) has been used as *process constraints.* In this way, only the model representations consistent with our knowledge about the functioning of the system, are retained (Gharari *et al.*, 2014b; Hrachowitz *et al.*, 2014).

Previous studies of hydrological modelling in Central America based on additional information are rare. Westerberg *et al.* (2014) use flow-duration curves to constrain their model for 32 regional catchments and found a clear relationship between local model performance and dataset consistency. They also found that regionalised flow duration curves were useful as a basic signature constraint for ungauged basins, but that additional constraints would be useful to further limit predictive uncertainty. Westerberg and Birkel (2015) used the base-flow index in addition to flow-duration curves and found that the types of signature information needed to constrain predictive uncertainty depended on the model structure (e.g. groundwater parameterisations with/without threshold-type behaviour).

Study areas and data

Central America

Central America is located near the equator, and is a narrow piece of land delimited by the Caribbean Sea to the east and the Pacific Ocean to the west (*Figure 1*). Climate variability in the region is largely shaped by the natural variations of precipitation taking place at the intra- and inter-annual time scales. Additionally, climate has a high spatial heterogeneity as a result of the interaction between the predominant atmospheric flow and the mountain ranges that cross the isthmus (Portig, 1965; Hastenrath, 1967). This interaction results in two main annual precipitation regimes, the Pacific and Caribbean types of climate, referring to which side of the slope they occur. The Pacific type of climate has an annual regime of precipitation that follows a bimodal distribution (*Figure 2*), with two maxima normally in June and September (Alfaro, 2002a). The dry season on the Pacific side is well defined and extends approximately from December to April. The annual precipitation distribution is modulated by the north-south migration of the ITCZ, the direct and indirect influence of tropical storms, the passing of easterly waves, low latitude cold air intrusions and other perturbations associated with the ITCZ (Amador *et al.*, 2006). A relative minimum of precipitation period occurs during July/August, and is commonly referred to as the Mid-Summer Drought (Magaña *et al.*, 1999). Contrary to the Pacific slope, the Caribbean type of climate does not present a well-defined dry season (Alfaro *et al.*, 1998). For both types of climate, discharge closely follows the precipitation regime (see e.g. *Figure 2*). In general terms, average air surface temperature (T_{avg}) show small variations at the intra-annual scale (Portig, 1965).

At the inter-annual scale, the climate of Central America has been linked to the SSTs anomalies of the surrounding oceans of the east equatorial Pacific through teleconnection mechanisms. These anomalies, quantified through its climatic index El Niño Southern Oscillation (ENSO), have been found to have a strong correlation that results in drier (wetter) conditions during a warm (cold) phase of ENSO in the Pacific slope (Waylen *et al.*, 1996a; Alfaro, 2014). Studies have also associated the combined state of the SSTs anomalies of the east equatorial Pacific (ENSO) and the Tropical North Atlantic (TNA) to inter-annual variations of precipitation and T_{avg} (Alfaro *et al.*, 1998; Enfield and Alfaro, 1999; Alfaro, 2002; Paper **I**). Thus, when the SSTs anomalies of the eastern tropical Pacific and the tropical Atlantic have the same sign, these are highly correlated with the anomalies of T_{avg}. Conversely, precipitation anomalies in the region are correlated when the SSTs anomalies have opposite sign. In this way, warmer (colder) SSTs in the Tropical Atlantic compared with those of the eastern tropical Pacific are linked to wetter (drier) than normal conditions in the Pacific Slope. In addition to the surrounding SSTs, there is a feature commonly referred to as the Caribbean Low-Level Jet (CLLJ, (Amador, 1998, 2008). The CLLJ is an area of strong winds that develops in the central part of the Caribbean Sea. Amador (2008) and Hidalgo *et al.* (2015) found that a stronger-than-normal CLLJ is associated with less precipitation in the Pacific Slope of Central America. Hidalgo et al. (2015) found that stronger (weaker) CLLJ was linked to northern latitudinal positions (with respect to its normal position), which results in less (more) precipitation on the Pacific Slope of Central America.

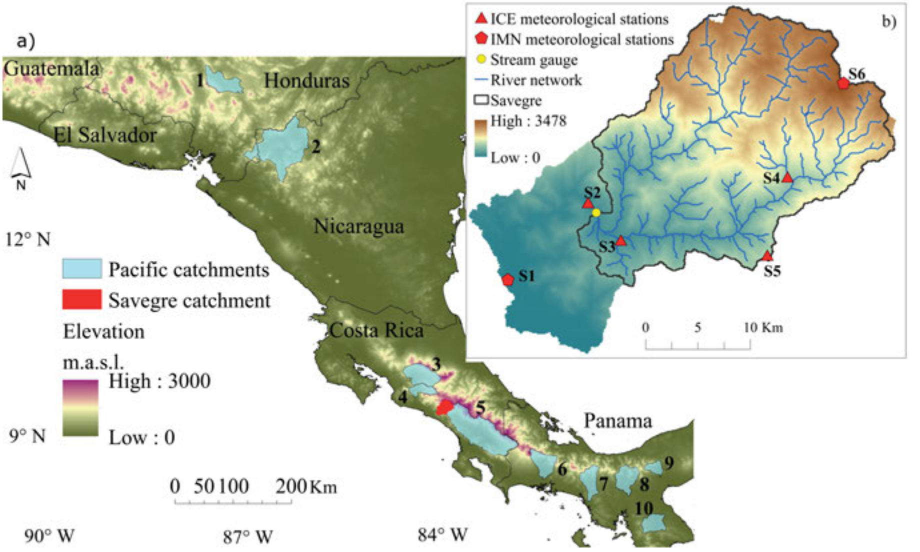

Figure 1. a) Location of the Savegre catchment (Papers II and IV) and ten catchments used to develop climate-variability constraints (Paper II), b) elevation profile of Savegre, the location of the meteorological stations used to obtain the catchment average precipitation series and the location of the stream gauge.

At inter-decadal scales other climatic phenomena such as the Pacific Decadal Oscillation (PDO; Mantua *et al.*, 1997) and the Atlantic Multidecadal Oscillation (AMO, Enfield *et al.*, 1999; Maldonado *et al.*, 2016) have also been associated to precipitation variability.

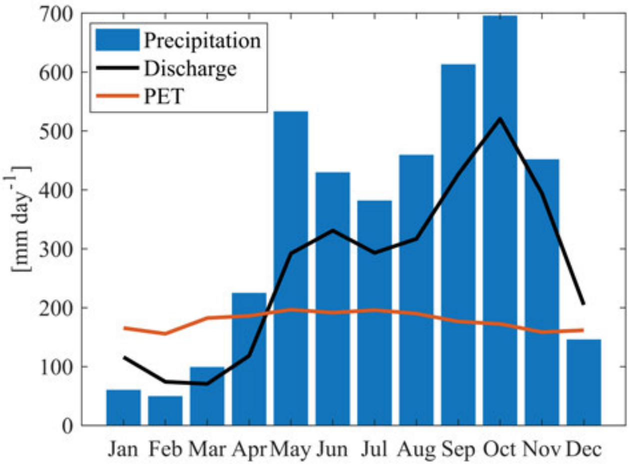

Figure 2. Average water balance of the Savegre catchment (located on the Pacific slope of Costa Rica) for the period 2000–2014.

Regional and global hydro-climatic datasets

In this thesis, several different regional and global hydro-climatic datasets are used (Table 2). The datasets are:

- Global maps of river discharge characteristics (Beck *et al.*, 2015).
- A monthly gridded temperature dataset by the Climate Anomaly Monitoring System (CAMS; Fan and van den Dool, 2008).
- Gridded precipitation data at 2.5° latitude (lat.) x 2.5° longitude (lon.) spatial resolution from Chen *et al.* (2002).
- A monthly gridded precipitation dataset obtained from the Climate Hazards Group InfraRed Precipitation with Station data with 0.05° lat. x 0.05° lon. spatial resolution (CHIRPS version 2.0, Funk *et al.*, 2014).
- A monthly precipitation station dataset provided by the Centro de Investigaciones Geofísicas from the Universidad de Costa Rica (CIGEFI-UCR dataset).
- Climate indices: ENSO, TNA, PDO, AMO, and the zonal winds to characterise the CLLJ annual strength, obtained from the Physical Sciences Division of the National Oceanographic and Atmospheric Administration/Oceanic and Atmospheric Research /Earth System Research Laboratory (PSD/NOAA/OAR/ESRL).
- A monthly gridded precipitation dataset produced by the Centro de Ciencias de la Atmósfera de la Universidad Autónoma de México (Magaña *et al.*, 1999, 2003), with 0.5° lat. x 0.5° lon. spatial resolution (CRN073).
- A monthly gridded precipitation and temperature dataset produced by the Climatic Research Unit at the University of East Anglia (CRU), with 0.5° lat. x 0.5° lon. spatial resolution (Harris *et al.*, 2014).

- A monthly gridded precipitation and temperature dataset (reanalysis) produced by the European Centre for Medium Range Weather Forecasts, with 0.5° lat. x 0.5° lon., spatial resolution (ERA-Interim, (Dee *et al.*, 2011).
- Monthly streamflow (gauges) from Global Runoff Database from the Global Runoff Data Centre (GRDC, 2013).
- Gridded daily and monthly T_{avg} data at 0.5° lat. x 0.5° lon. spatial resolution from Maurer *et al.* (2009).

Gridded T_{avg} and precipitation data at 0.5° lat. x 0.5° lon. spatial resolution from the National Center of Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalysis (Kalnay *et al.*, 1996).

Table 2. *The regional and global datasets used in this thesis.*

Dataset	Data type	Paper **I**	Paper **II**	Paper **III**
(Beck *et al.*, 2015)	Q statistics (gridded)		X	
CAMS	T (gridded)	X		
CHEN	P (gridded)	X		
CHIRPS	P (gridded)	X	X	X
CIGEFI-UCR	P (station)	X	X	X
Climate index	ENSO, TNA, PDO	X	X	
CRN073	P (gridded)		X	X
CRU	P &T (gridded)	X	X	X
ERA-Interim	P & T (gridded)			X
GCM (projections)	P & T (gridded)	X		
GRDC	Q (flow gauges)	X		
(Maurer et al., 2009)	T (gridded)	X		

The Savegre River catchment

The Savegre catchment was used to test the methodologies developed in Paper **II** and Paper **IV**. This catchment is located on the Pacific side of Costa Rica (*Figure 1*). The Savegre catchment has an area of 468 km^2 and has a steep terrain with elevations in the range of 142 m (location of the stream gauge) to 3478 m. Land cover is mainly natural forest, while pasture and agriculture cover a smaller area. The mean annual precipitation is 4138 mm/year (period 2000–2014, *Figure 2*) and the mean temperature is approximately 21°C, however, the elevation gradient results in wide spatial variation of temperatures (14°C – 27°C). The catchment has a tropical monsoon type of climate (Köppen-Geiger Am-climate). Mean annual runoff is 3149 mm/year and mean annual potential evapotranspiration (PET, calculated with Oudin formula, Oudin *et al.*, 2005) 1450 mm/year. Daily streamflow data for the Savegre were obtained from the Instituto Costarricense de Electricidad (ICE) for the period 2000–2014. Precipitation data were obtained from stations operated by ICE and the Instituto Meteorológico Nacional (IMN, *Figure 1b*). Mean base-flow index for this catchment was 0.86 (calculated using the base-flow separation method by Gustard *et al.*, 1992).

Methods

In order to reach the ultimate goal of risk reduction associated to hydro-climatic variability extremes in Central America, this thesis used the different steps schematically described in *Figure 3*. Hydro-climatic (air temperature) data were developed in Paper **I** and used to improve understanding of climate variability processes. Knowledge about climate variability (partly obtained from Paper **I**) was used in Paper **II** to develop a method to reduce uncertainties in simulated river discharge data in ungauged catchments and in that way allowed studying hydrological variability. Papers **III**-**V** focused on extremes associated to hydro-climatic variability. In Paper **III** different combinations of drought indices and meteorological datasets were assessed in order to find the most suitable for drought characterisation. In Paper **IV** a method was developed for automating hydrological drought typology and improving understanding of drought propagation in tropical catchments. Finally, in Paper **V**, a method was developed for consistent assessment of change in hydrological extremes.

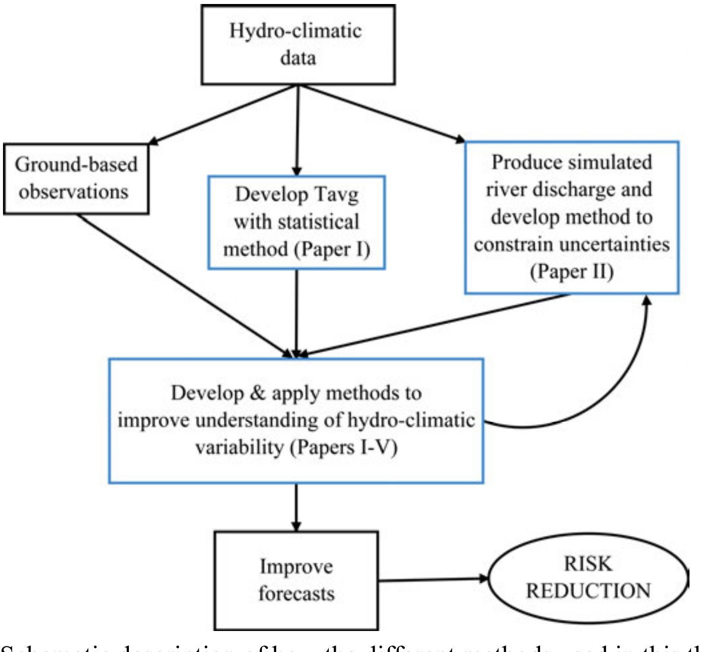

Figure 3. Schematic description of how the different methods used in this thesis contribute to reach the ultimate goal of risk reduction.

Reduction of hydro-climatic data uncertainties

New high-resolution temperature dataset

A new high-resolution T_{avg} dataset was developed for the region of Central America (Paper **I**). The procedure to obtain the data was a modification of the method called PRISM (Daly *et al.*, 1994, 2002, 2008), which was developed to obtain interpolated climate data in physiographic complex terrain. For this, station data and the gridded Maurer *et al.* (2009) dataset were used to obtain a gridded daily temperature dataset at a spatial resolution of 5 km. The low-resolution dataset was used when there was no station data available in a given region. The largest assumption in PRISM and the modification of PRISM used in this application, is that for a given location, spatial temperature variations are mostly controlled by elevation (Daly *et al.*, 2002). Thus, at a desired grid point, a weighted linear regression was done between nearby station data and elevation. The weights account for other more complex relationships between temperature and different variables. Thus, the weights at a given grid point were defined according to:

- The distance from the station, W(d).
- Its elevation, W(z).
- The number of stations within a specified radius, or cluster, W(c).
- Defining two layers with respect to the temperature inversion elevation, a weight was defined depending on whether the grid point is in the same layer as the station, W(l).
- Topographic facet, W(f), which identifies climatic patterns depending on common topographic slope characteristics (e.g. if the station is located in the north-facing side of the mountain).
- Coastal proximity, W(p).
- Effective terrain, W(e), which reflects how the terrain affects temperature (those stations on similar terrain, are similarly weighted).

The final weight for a station, W, was obtained using the following equation:

$$W = [0.8W(d)^2 + 0.2W(z)^2]^{1/2}W(c)W(l)W(f)W(p)W(e)$$

Reduction of uncertainties in hydrological model simulations for ungauged catchments

A methodology was developed to reduce uncertainties in simulated long-term discharge data in ungauged catchments in Central America (Paper **II**). The method used additional information in the form of expert knowledge about climate variability. The rationale behind this approach is the strong relationship between climatic and hydrological variability in the region. Thus, it is possible to know certain aspects of the hydrological-variability behaviour that the model should represent beforehand, in agreement with the known behaviour of the climate variability. The methodology was developed and evaluated in the Savegre catchment (*Figure 1*), which was treated as ungauged.

The HBV-light model (Seibert and Vis, 2012) was used to obtain daily river discharge data for the period 2000–2014. The model was run 1,500,000 times using parameter sets randomly sampled from previously defined parameter ranges. An initial rejection was done to parameter sets that did not agree with the understanding of the system functioning (i.e. parameter constraints were applied). To this resulting distribution, four process constraints were used to further constrain the parameter space. The process constraints were applied similar to limits of acceptability in the extended GLUE methodology (Beven, 2006) and all model parameters that failed to represent these process characteristics (i.e. for which simulated behaviour was outside the limits) were rejected. The four process constraints were the following:

1. A long-term climate impact constraint: based on the link between long-term climate and water balance characteristics, as quantified by the Budyko curve. This curve describes the relationship between the aridity index calculated as PET/P and the runoff ratio calculated as Q/P (where Q is discharge and P precipitation). Limits of acceptability were defined based on information about the Budyko relation in the region from empirical data analysed by Westerberg *et al.* (2014).
2. Inter-annual climate variability constraint: based on the link that different climate phenomena and precipitation exert on discharge in the region. The link between annual values of climate variability indices ENSO, TNA, TNA+ENSO, TNA-ENSO, CLLJ, as well as annual precipitation data were correlated with annual discharge to explore which of these showed the highest connection. The index/data with the highest value was then used to reject those parameter sets for which inter-annual climate–discharge variations disagreed.
3. Intra-annual climate variability constraint: based on the strong relationship between monthly precipitation and discharge at the monthly scale during the wet-season months. Those parameter sets for which discharge did not follow the intra-annual variations of precipitation during those months, were rejected.
4. Low-flow statistics constraint: based on a global map of the 99th exceedance percentile of daily discharge (Q_{99}) and its associated uncertainty obtained from Beck *et al.* (2015).

To develop the limits of acceptability of constraints 2 and 3, an analysis was done between climate variability and precipitation in 10 Central American catchments (*Figure 1a*).

The usefulness of the methodology was evaluated in terms of the ability of the model to reproduce the observed hydrograph and the active catchment processes in terms of two efficiency measures (efficiency and reliability), and 17 hydrological signatures. The signatures were selected to evaluate how the model represented water balance and flow distribution. In addition, the constrained model was compared to a traditional calibration using the automatic genetic optimisation algorithm (GA) included in the HBV-light model.

Improving understanding of hydro-climatic variability and change processes

Climate variability analysis with new average air temperature data

The climate variability analysis comprised two parts (Paper **I**). The first part was an analysis of trends in annual precipitation and temperature for the period 1970–1999 using the Mann-Kendall test. The trends in both variables were calculated with high and low-resolution datasets, in order to assess the improvement of information provided by the new dataset. The high resolutions datasets were CHIRPS for precipitation and the high resolution T_{avg} data developed in Paper **I**. The lower resolution data were CAMS, CRU and NCEP/NCAR for temperature, and NCEP/NCAR and the CHEN dataset for precipitation.

The second part of the analysis was a temperature- and precipitation-variability analysis in which their principal modes of variability were associated with large-scale climatic phenomena, ENSO, TNA, CLLJ, PDO and AMO.

Climate change application with new average air temperature data

A brief climate-change application was included to show an example of an additional use of the new T_{avg} dataset produced in Paper **I**. The dataset was used together with the high resolution CHIRPS precipitation data to downscale future climate projections from fourteen Global Climate Model (GCM) runs to a spatial resolution of 0.05º latitude x 0.05 º longitude. The downscaling procedure was done with a modification of the Bias Correction and Spatial Disaggregation procedure (Wood *et al.*, 2004). Thus, relationships were obtained between temperature patterns at the high resolution with the low resolution ones for the period 1979–1999. These relationships were then applied to downscale projected temperature and precipitation data for the period 2000–2049. Then, average values for both variables were compared at a baseline climate scenario (1979–1999) and a projected scenario (2019–2049).

Drought propagation in a tropical catchment

To study drought propagation processes in the tropics we used as a case study the Savegre catchment in Costa Rica (*Figure 1*) (Paper **IV**). The analysis consisted first of identifying all drought events in precipitation, river and base flow. For this, the threshold-level method (Yevjevich, 1967) was used based on a threshold using the 80th exceedance percentile of the daily series of the variable in question. After having identified the drought events, these were plotted together with the time series of each variable to make an initial visual analysis of drought propagation. This step allowed identifying the different causes and characteristics of the hydrological drought events (manual typology, an automatic typology is described below). Then, it was verified if these drought propagation processes agreed with the ones in the hydrological drought typology described by Van Loon and Van Lanen (2012). Finally, drought propagation characteristics were studied in terms of duration, timing and deficit indicators, to study the pooling, lag and lengthening patterns in this catchment.

Data and methods for assessment of hydro-climatic extremes

Evaluation of data and methods for drought characterisation in Central America

An evaluation of different combinations of meteorological datasets and meteorological drought indices was made in order to find the most suitable one for drought characterisation in Central America (Paper **III)**. The evaluated indices were SPI, deciles, SPEI and EDI. These were calculated using precipitation data from CHIRPS, CRN073, CRU, ERA-Interim and a regional station dataset, and temperature from the CRU and ERA-Interim datasets.

First, an assessment was done of the meteorological data, in terms of how well they captured key climate features of the region. This assessment was based on Spearman rank correlations between ground-based precipitation data at 24 study points, and the closest grid point from the gridded datasets. Then, the different combinations of drought indices and datasets were evaluated using independent river discharge data, through the calculation of the Standardised Streamflow Index (SSI). This was done at five catchments, which were selected based on their locations at non-regulated streams, their relative proximity to the meteorological stations used in this study, and that simulated data from the study of Westerberg *et al.* (2014) were available to fill data gaps. The evaluation was done through Spearman correlation between the four indices and the SSI, and the Peirce skill score (P_{SS}; Peirce, 1884). For the P_{SS}, a contingency table was calculated where hits, misses, false alarms and correct negatives were defined, with respect to the events identified by the SSI. Finally, an ANOVA table was used to compare the performances of the different datasets and indices at the five accumulation times.

Automation of hydrological drought typology for a Costa Rican catchment

A methodology was developed to provide an automated, objective drought typology to analyse drought propagation in the tropics, according to the typology of Van Loon and Van Lanen (2012) in Paper **IV**. For this, a set of criteria was defined to classify CR, wet-to-dry season drought and composite hydrological droughts. These criteria were then integrated into an if-else-statements algorithm in *Matlab*. The algorithm is summarised in *Figure* 4 (see Appendix, Paper **IV**). We tested the typology in the Savegre catchment against a manual typology (see section above).

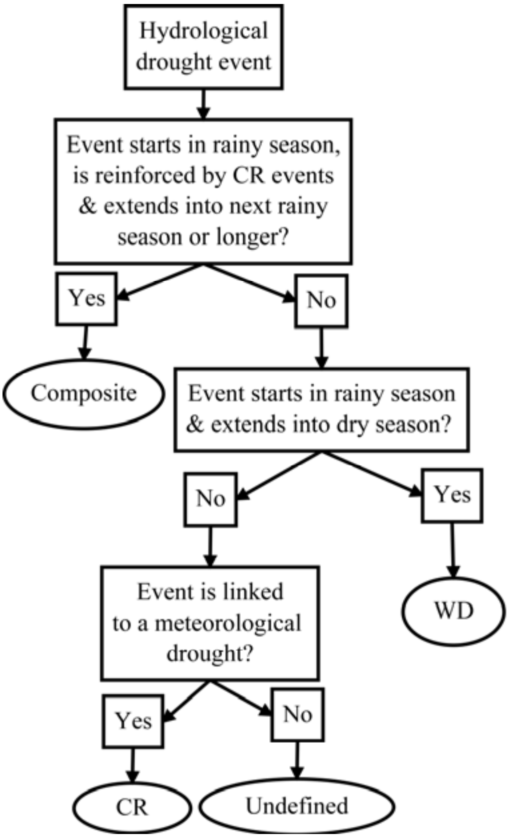

Figure 4. Summary of steps to develop the automation of drought typology (Paper **IV**). CR refers to classical rainfall deficit drought, and WD to wet-to-dry season drought.

Assessment of hydrological extremes with a consistent framework

A methodology was proposed to overcome the limitations of the most commonly used methodologies that assess changes in hydrological extremes (Paper **V**). The methodology was designed to study both hydrological extremes in a consistent way. For this, both floods and droughts were defined using the threshold-level method. A drought (flood) event occurred when the flow value was below (above) a predefined threshold. Several characteristics were included in the assessment of changes in extremes: frequency, duration and surplus/deficit volume of the events. These characteristics provide information that not only can be useful for assessment of changes in extremes, but also useful for decisions within water and disaster management.

Two versions of the consistent methodology were analysed. In the first one, a fully symmetrical calculation of the threshold for both extremes was used. Thus, droughts (floods) were defined by a threshold based on the 99th (1st) exceedance percentile of the monthly time series. In the second analysis, floods were defined using a threshold based on the 1st exceedance percentile of the daily series, while droughts were defined using a monthly varying threshold based on the 80th exceedance percentile of the monthly series. This second analysis is a less symmetrical version of the first one, but given that it is based on only one methodology, it is still consistent. In addition, the design of this second analysis reflects the most common ways to study hydrological extremes, which are impact-focused (e.g. Fleig *et al.*, 2006; Burn *et al.*, 2016).

An application example of the consistent methodology was done for the Po River catchment, in Italy. This catchment was selected because a long and good-quality hydrological data series is available. Additionally, several studies have reported changes in hydrological extremes in the catchment (e.g. Kottegoda and Natale, 1994; Zanchettin *et al.*, 2008; Di Baldassarre *et al.*, 2009). Most of these changes have been attributed to the fast industrial and agricultural expansion, and urbanisation that the country experienced in the 1960s. On one hand, the catchment has experienced an increase in flood peaks, attributed to the building and heightening of levees over the past two centuries by Di Baldassarre *et al.* (2009). On the other hand, the catchment has experienced a decrease in annual minimum flows in the lower part of the river, attributed to water consumption by irrigated crops after the rapid expansion of irrigation that took place in the second half of the 19th century (Kottegoda and Natale, 1994).

In the application of the methodology, data from two streamflow stations, Pontelagoscuro (downstream) and Piacenza (upstream) were used, with contributing areas of 42,000 km^2 and 71,000 km^2, respectively. The period of 1924–2009 was selected, since earlier than that, in the 1920s, a major precipitation shift has been reported (Zanchettin *et al.*, 2008). To assess the (potentially) human-induced changes, this period was split into two: 1924–1953 (*baseline*) and 1980–2009 (*human influenced*). Then, flood and drought thresholds were obtained for each station for the baseline period, and then applied to both the baseline and human-influenced periods. Thus, it was assumed that the differences found in the characteristics of extremes between these two periods were mostly due to human activities.

Results

Reduction of hydro-climatic data uncertainties

New high-resolution air temperature dataset

With the modified version of the PRISM methodology it was possible to obtain a high-resolution temperature dataset for the Central American region. The long-term average T_{avg} patterns showed more details of the spatial variations than the existing gridded datasets. As expected, these spatial patterns were strongly influenced by elevation (*Figure 5*). With the new dataset it was possible to see that the seasonal variations of T_{avg}, represented by long-term averages of January and July in *Figure 5*, had, in general, higher (spatial) variability in the northern part of Central America than in the south.

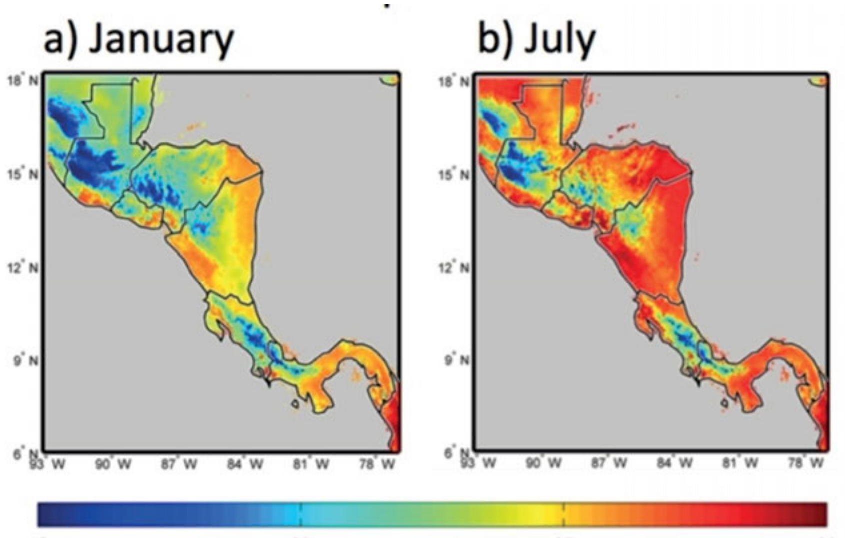

Figure 5. Mean air temperature (°C) for the months of January and July for the period 1970–1999 (Paper **I**).

Hydrological simulated data with constrained uncertainties

From a total of 1.5 million parameter sets, 84% were discarded after applying both parameter and process constraints. The parameter constraint was most effective in terms of number of parameter sets, 52% of the prior distribution was discarded after it was applied. However, for the parameter constraint no specific model representations were rejected, but with the process constraints it was possible to reduce different aspects of the simulated model uncertainty.

From the four process constraints, the Q_{99} constraint that was based on (hard) discharge information provided the largest reduction of parameter sets and of inconsistent process representations (as seen in the signature evaluation). Most of the rejected representations had to do with too low variability of flow, too high values of base-flow index, and inconsistent slow-responding representations (some of these are shown in *Figure 6*). The climate variability constraints discarded a much smaller number of parameter sets than the Q_{99}, which suggests that the climate variability information was not that useful. However, the hydrological signature analysis showed that the climate variability constraints rejected inconsistent representations of the system that the Q_{99} did not reject (mostly inconsistent groundwater representations). The CLLJ climate index, together with annual precipitation, showed the highest correlation with discharge, and was used at the inter-annual scale. The results showed that both precipitation and CLLJ had the same constraining effect. From all the climate variability constraints, the intra-annual constraint was most useful for reducing model uncertainty.

The predictive range was substantially reduced at monthly and annual time scales after applying all the constraints together (*Figure 7*). During 2005 and 2006 the simulated uncertainty was too constrained and it did not include the observed values, however, the optimised model showed the same pattern which may therefore indicate model-structure or data-related problems. At daily, monthly and annual scales the median of the final constrained distribution was close to the observed and the GA-optimised simulated hydrographs.

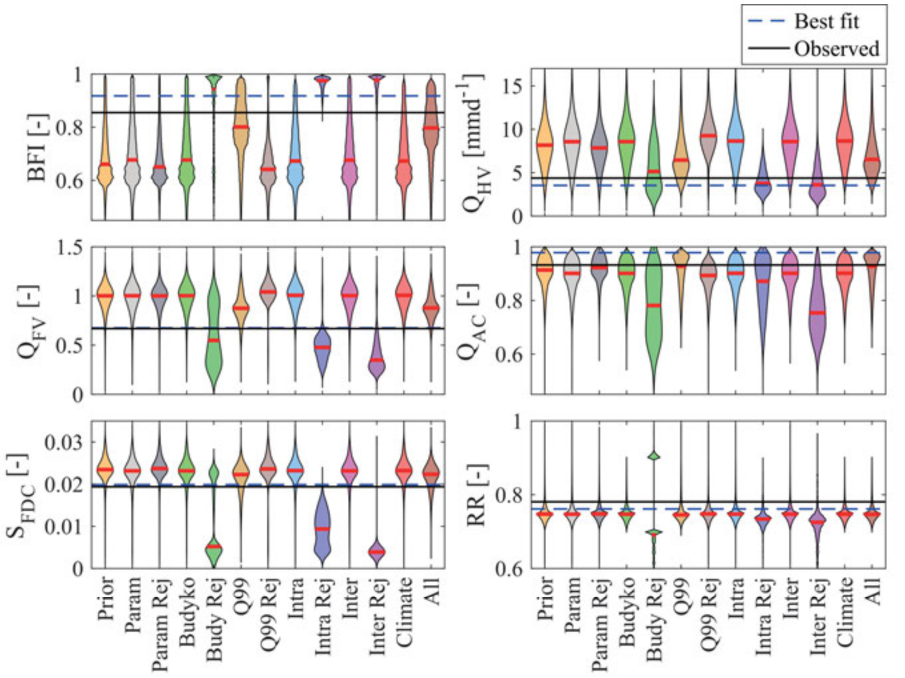

Figure 6. Violin plots of the distribution of hydrological signatures calculated using the model realisation for the prior, the parameter constrained (Param) and the process-constrained parameter distributions (Budyko, Q99, Intra and Inter). The combined effects of all the parameter and climate process constraints (Climate) and all the constraints together (All) are also shown. For each constraint there is a violin plot of the rejected values (labelled as the name of the constraint plus 'Rej'). The violins cover 100% of the distribution, but the y-axes were adjusted to show the main part of the distributions. The median for each distribution is shown in a red line across each violin (Paper **II**).

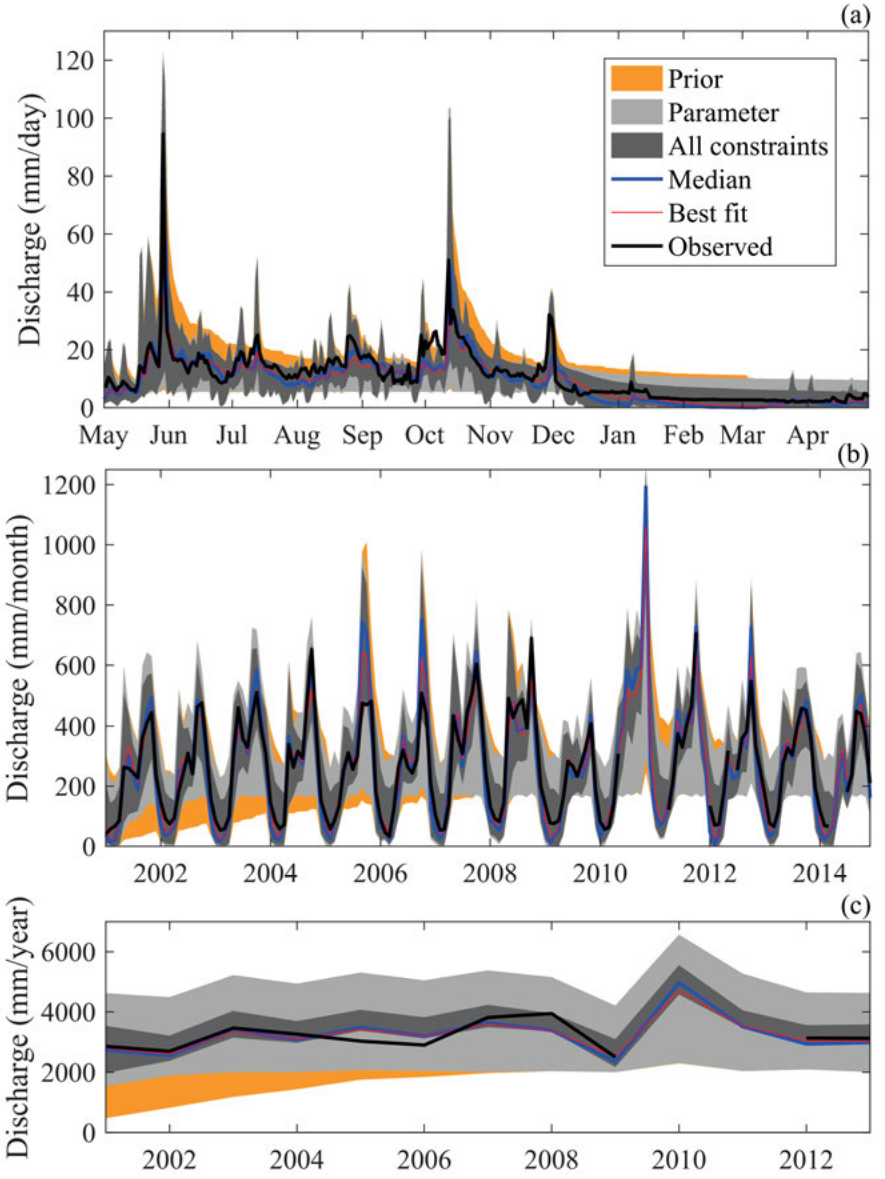

Figure 7. 100% prediction range of the discharge for the prior, parameter-constrained posterior and the posterior distributions after applying all the constraints at a) daily (year 2008), b) monthly and c) annual time scales. The median of the distributions for the different constraints are shown in blue, the observed in black and the best fit for the optimised model in red (Paper **II**)

Hydro-climatic process understanding

Climate variability and change analyses with new average air temperature data

Climate variability and change analysis were done with the new high-resolution T_{avg} data developed in Paper **I**. Results showed that trends in annual T_{avg} were statistically more significant than trends in annual average precipitation (*Figure 8*). A large part of Central America showed significant temperature trends. These trends were increasing for most of the northern part of the region, and a large part of Costa Rica and the Caribbean coast of Nicaragua, and decreasing for parts of Honduras and Panama. Unlike the spatial patterns of long-term temperature averages (*Figure 5*), these trends did not seem to be influenced by the terrain. Precipitation trends were only significant in a small part of the region, showing positive sign in the southern Caribbean coast of Costa Rica, and Guatemala, El Salvador and Panama (though smaller). Negative trends, i.e. drying trends, were found in the Central Pacific slope of Costa Rica and a small region in Panama.

The correlation of the variability of precipitation and temperature with the different climate indices revealed that:

- ENSO was correlated with precipitation in the Pacific slope of Central America, with drier (wetter) conditions during a warm (cold) phase of ENSO.
- ENSO was positively correlated with T_{avg} across the region.
- TNA was positively correlated with precipitation across the region.
- ENSO-TNA was highly correlated with precipitation in most of the region.
- ENSO+TNA was highly correlated with T_{avg} in most of the region.
- The CLLJ had high correlation with precipitation and low with T_{avg} over the region.
- AMO and PDO had correlation with variations at longer scales (inter-decadal).

The high-resolution dataset produced in Paper **I** was useful for downscaling GCM-projected data. The comparison of precipitation and (downscaled) temperature between the baseline and projected climate scenarios showed drier conditions in the future in the northern part of Central America, and wetter conditions in Panama. Warmer temperatures were shown for most of Central America.

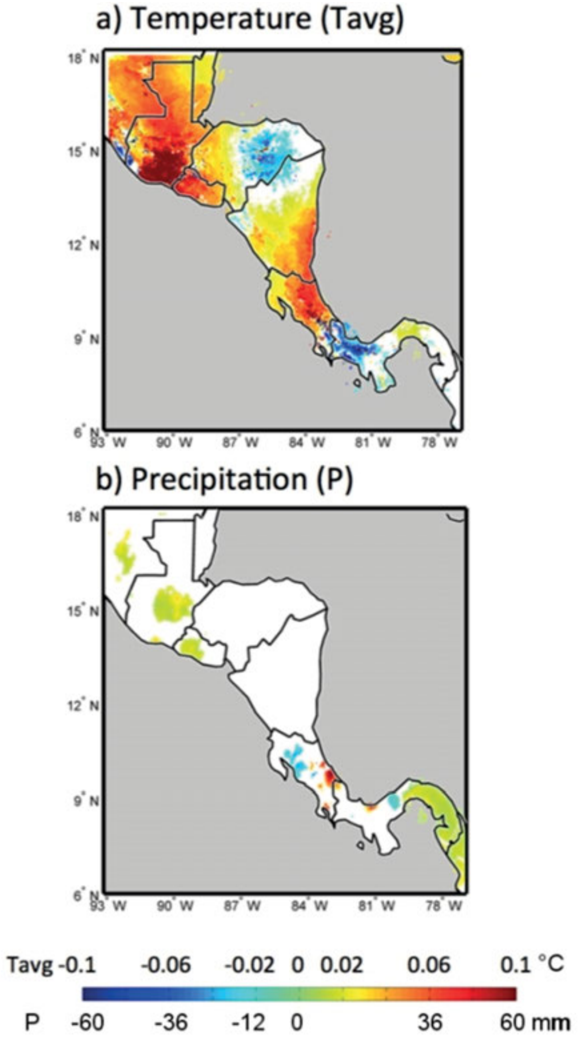

Figure 8. Annual trends (1970–1999) of average temperature in °C yr^{-1} (top) and precipitation in mm yr^{-1} (bottom). Only significant trends at the p=0.05 level are shown (Paper **I**).

Drought propagation in a tropical catchment

In the Savegre catchment, it was possible to see drought propagation in terms of pooling and lengthening when moving from precipitation, to river discharge and base flow (*Figure 9*). However, for some CR events occurring in the rainy season, the differences in duration were not so large. Deficit volume values for river discharge and base-flow droughts were rather similar, and these were often larger than precipitation deficits.

The processes causing hydrological droughts in the Savegre catchment could be explained by those described in the typology developed by Van Loon and Van Lanen (2012), i.e. those of CR, wet-to-dry season and composite droughts. Overall, meteorological droughts were numerous and short. There was also a high number of hydrological droughts (though more for river discharge than for base flow) and most of these events were relatively short and occurred as a direct response to rainfall deficits, with a short lag (*Figure 9*). Most of the hydrological droughts were of CR type, specifically 80% for river discharge and 76% for base flow (Table 3). However, a few season and composite events were also identified (Table 3, *Figure 9*).

Table 3. *Hydrological drought typology for the Savegre catchment. CR refers to classical rainfall deficit droughts, WD refers to wet-to-dry season droughts and Comp. to composite droughts.*

Droughts in	Typology	CR	WD	Comp.	Undefined	Total number of events
Precipitation		-	-	-	-	101
River discharge	Manual	32	0	2	6	40
	Automatic	33	0	2	6	41
Base flow	Manual	19	0	3	3	25
	Automatic	19	0	3	4	26

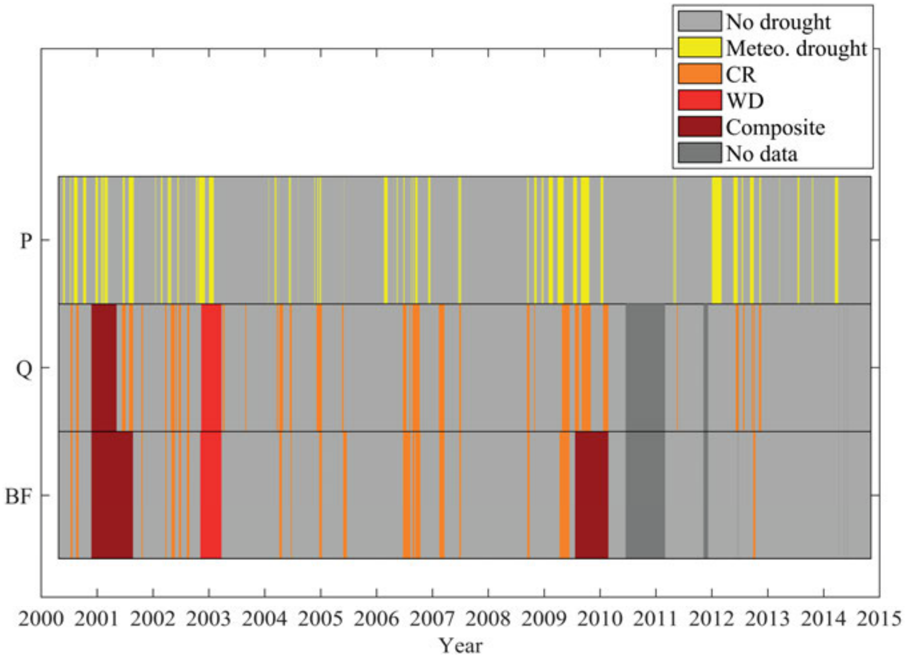

Figure 9. Timing of the drought events identified in precipitation (P), river discharge (Q) and base flow (BF) in the Savegre catchment for the period 2000–2014 (Paper **IV**). CR refers to classical rainfall deficit droughts and WD refers to wet-to-dry season droughts.

Data and methods for assessment of hydro-climatic extremes

Combination of meteorological dataset and drought index

All assessed regional and global precipitation datasets were able to capture important climatic features such as the bimodal distribution typical of the Pacific slope. However, for the Caribbean the variability was less well captured. When looking at the monthly median precipitation values, there were large differences between the datasets, sometimes even of 100%. The correlations made at each of the 24 study points revealed that CHIRPS and CRN073 were best at capturing the spatial patterns at intra- and inter-annual scales. Important events reported in the media, such as that occurring in 1997 on the Pacific slope of Central America, were captured by all the indices. Some important features were better captured by the CHIRPS dataset, e.g. the wet event in the Caribbean side of Costa Rica during the 1997 Pacific slope drought. The differences between the different datasets were large. The Spearman rank correlation was significantly higher when comparing the same dataset to calculate different drought indices (all values above 0.9 at a 0.95 significance level) than when comparing the same index using different datasets (values between 0.45 and 0.57 at a 0.95 significance level).

The results of the correlations between all the combinations (drought index and meteorological dataset) and SSI, showed that CHIRPS performed best and it was followed by the station data and CRN073. Similar results were found with the P_{SS} analysis. On the other hand, for both the correlations and the P_{SS}, CRU and ERAI were the worst performing datasets. In terms of drought index, the DI resulted in the highest P_{SS} and the SPI in the highest Spearman correlations. SPEI was only calculated with the CRU and ERAI datasets, but in terms of correlation it outperformed both SPI and DI, indicating that temperature is important for drought characterisation.

Automation of drought propagation

The algorithm developed for the automatic, objective hydrological drought typology was successful in reproducing the manual typology in the Savegre catchment. One river discharge drought was identified as CR by the automated typology and as 'undefined' by the manual typology. In the manual typology, it was possible to assess that a large rainfall event occurring after a meteorological drought hindered the generation of hydrological drought. The automation, unable to make this assessment, linked the meteorological drought as a cause of the river discharge drought. Another mismatch was a hydrological drought identified as undefined by the automation. In the manual typology, this event was pooled with a previous composite hydrological drought since these two seemed to have the same causing mechanisms. In the automation, these two events were not pooled, and thus, the algorithm classified it as undefined when it could not identify any cause.

Methodology to consistently assess changes in hydrological extremes

In the example application, the analysis done with the consistent framework in its two versions, revealed an exacerbation of both floods and droughts in terms of duration and magnitude, i.e. surplus/deficit volume (*Figure 10*). In the consistent approach using symmetrical thresholds, flood and drought events were less frequent and had higher magnitude at both upstream and downstream stations during the human-influenced period, with the downstream station showing a much larger difference in surplus/deficit volume (Table 4). For floods, the impact-based version of the consistent analysis was able to capture higher frequencies and magnitudes during the human-influenced period than in the reference period (Table 5). In terms of drought trends with the impact-focused analysis, the differences between Piacenza and Pontelagoscuro were limited (Table 5).

The threshold-level method was able to capture the most important flood events reported in the literature (Zanchettin *et al.*, 2008; Montanari, 2012).

Table 4. *General statistics of the consistent approach example application. Droughts (floods) were defined on a monthly timescale based on the 99th (1st) exceedance percentile of the total time series. For each characteristic, the relative change with respect to the baseline period is included in parenthesis.*

	Piacenza 1924–1953	Piacenza 1980–2009 (% change)	Pontelagoscuro 1924–1953	Pontelagoscuro 1980–2009 (% change)
Flood events (number)	4	2 (-50%)	4	3 (-25%)
Flood duration (average) [months]	1	1.5 (50%)	1	1.3 (33.3%)
Flood volume (average) [mm]	42.5	60 (41.1%)	12.3	62.3 (404%)
Drought events (number)	4	3 (-25%)	3	1 (-66.7%)
Drought duration (average) [months]	1	2 (100%)	2	2 (0%)
Drought volume (average) [mm]	1.8	4 (118%)	0.9	6.6

Table 5. *General statistics of the impact-focused approach application example. Floods were defined on a daily timescale with a fixed threshold based on the 1st percentile. Droughts were defined based on a monthly varying threshold based on the 80th percentile. For each characteristic, the relative change with respect to the baseline period is included in parenthesis.*

	Piacenza 1924–1953	Piacenza 1980–2009 (% change)	Pontelagoscuro 1924–1953	Pontelagoscuro 1980–2009 (% change)
Flood events (number)	39	45 (15.4%)	28	32 (14.3%)
Flood duration (average) [days]	2.8	2.6 (-5.3%)	3.9	4.9 (26.8%)
Flood volume (average) [mm]	7	5 (-27.3%)	4.6	6.9 (49.8%)
Drought events (number)	36	38 (5.6%)	38	40 (5.3%)
Drought duration (average) [months]	2.0	2.3 (14.5%)	1.9	2.3 (21.4%)
Drought volume (average) [mm]	14.1	19.9 (41%)	14.8	17.7 (20%)

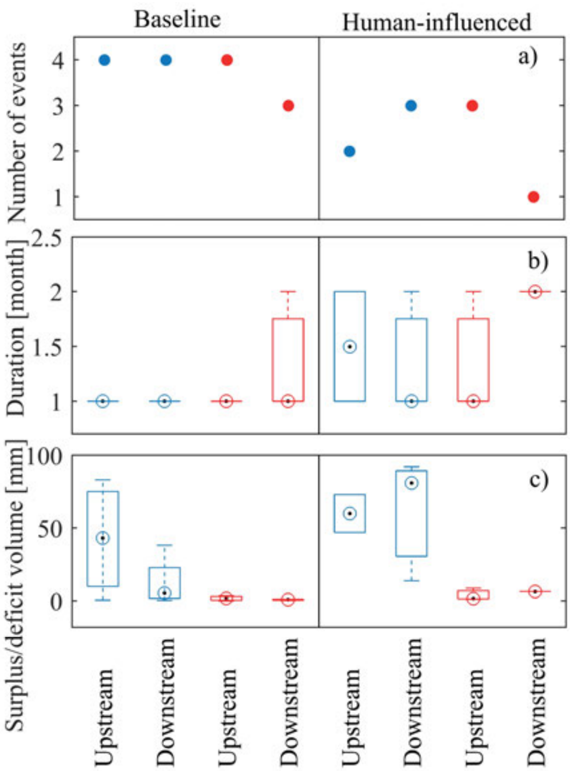

Figure 10. Boxplots showing the 100% distribution of the characteristics values for floods (blue) and droughts (red) obtained using the consistent approach in the example application. Droughts (floods) were defined on a monthly timescale based on the 99th (1st) exceedance percentile of the total time series. The boxplots cover the interquartile range (25th–75th percentile) and the median is shown by the marker.

Discussion

The work presented in this thesis is intended to support risk reduction of disasters associated with hydro-climatic extremes. This was done through several steps dealing with the improvement of available data and assessment methods.

Reducing data uncertainties to improve knowledge

New high-resolution T_{avg} data

The method used to develop the dataset was based on a climate-elevation regression and accounted for other important geographic features such as coastal proximity and topographic facets. These features have been found important in the shaping of spatial temperature patterns (Daly *et al.*, 2002). The results showed that the spatial patterns provided by this new dataset were highly detailed, and as expected, reflected the relationship between topography and temperature. These data therefore improved the state of knowledge provided by existing ground-based observation and global/regional datasets. The new knowledge not only consists of better understanding of temperature patterns per se, but also help improving knowledge about climate variability and its causing mechanisms. Thus, in Paper **I** these data were used, together with the already available CHIRPS precipitation data, in two climate variability analyses. One of these was a trend analysis for both variables, which showed more consistent and statistically significant results for temperature than for precipitation. Positive trends were found for a large part of northern Central America, and cooling trends in parts of Honduras and Panama. These results agree with a previous analysis using lower-resolution data by Hidalgo *et al.* (2013). The identified trends were, however, more detailed than with the lower-resolution datasets used in Hidalgo *et al.* (2013). This dataset has a potential to be used for e.g. forcing of a hydrological model to study the impact that these increasing T_{avg} values have on soil moisture and runoff through evapotranspiration.

The second part of the analysis explored the link between climate phenomena and climate variability in the region. For precipitation, results agreed with other studies (e.g. Enfield and Alfaro, 1999; Maldonado *et al.*, 2013) concluding drier (wetter) conditions when the SSTs indicated by the TNA index are cooler (warmer) than those indicated by ENSO. For temperature, results indicated that correlations were high and positive when the SSTs of the surrounding oceans had the same sign, rather than contrasting ones. Influence of the SSTs of the surrounding oceans and T_{avg} in the region has been reported by Alfaro (2002b) and Fallas-López (2014), but these have been done at lower spatial resolutions than the one presented in this thesis. Thus, climate-variability analyses agreed with the state of knowledge, but improved it with a higher level of spatial detail.

A climate change application was also included in Paper **I** as a way to show yet another use of the high-resolution T_{avg}. The high-resolution data were used to statistically downscale GCM-projected data. This suggests that more work is needed in studying the impact of changes in temperature in water resources in Central America with the help of a hydrological model. Such studies could be done at the catchment scale because of the spatial resolution of the dataset in combination with e.g. CHIRPS. It should be mentioned that these climate-change results are subject to different sources of uncertainty related with the GCM-model representation of processes and scenarios and the downscaling method that would propagate to the hydrological model, which itself has limitations. Thus, these conclusions have to be handled with care.

Reducing uncertainties in hydrological models in ungauged catchments

In Paper **III**, information about climate variability, a part of which was obtained in Paper **I**, was used to reduce the predictive uncertainty of a hydrological model for an ungauged catchment in Central America. The parameter constraint reduced the largest number of parameter sets, but no clear improvement in process representation was observed. The Q_{99} constraint led to the largest rejection of inconsistent catchment representations (observed discharge and hydrological signatures). It forced the model to increase the overall base-flow contribution, and reduce the underestimation of low flows. The discharge information was therefore more useful than the climate-variability information for constraining uncertainty. However, other inconsistent representations were only rejected by the climate-variability constraints, which shows that there is potential to use this type of knowledge for reducing uncertainties. The Budyko constraint on long-term water balance representation had an overall small, but positive effect on uncertainty reduction. The small effect compared to e.g. the intra-annual constraint could be related to the fact that Savegre is a humid catchment. Water-balance constraints have also been successfully applied in previous studies (Yadav *et al.*, 2007; Winsemius *et al.*, 2008; Gharari *et al.*, 2014b). At the inter-annual scale, the constraint was based on the connections that different climate phenomena can have with discharge in the region. The CLLJ showed the highest correlation values. When applied as a constraint, the CLLJ could not provide additional constraining information to that provided by annual precipitation. Thus, the influence of the CLLJ on discharge at the Savegre catchment seems to be merely related with the influence of the CLLJ on precipitation. The initial hypothesis was that the climate phenomena could influence discharge through other variables (e.g. wind forcing, evapotranspiration), but it is possible that such influences are negligible in a wet catchment such as Savegre. Thus, both the CLLJ and Budyko constraints should be futher evaluated in other drier catchments. The overall improvement of groundwater processes provided by the different process constraints, particularly the Q_{99} constraint, is encouraging for future studies, given the common limitations found in hydrological models to represent low flows (Smakhtin *et al.*, 1998; Engeland *et al.*, 2006; Engeland and Hisdal, 2009). Other (hard) discharge constraints should be included in the future, to constrain e.g. the representation of high and median flows. The Q_{99} constraint was found to be useful for this particular model structure, but it does not guarantee that it is useful for different model structures, since it has been found that the constraining effect of different types of information may depend on which model structure is used (Westerberg and Birkel, 2015).

Overall, the method improved model representation and substantially reduced the model predictive uncertainty. The method is therefore promising for simulating long-term flow data for ungauged catchments on the Pacific side of Central America. However, the method was developed and used in one catchment in Costa Rica, and it should be evaluated in other Central American catchments. In addition, it suggests that similar methods can be developed for ungauged basins in other regions where climate variability exerts a strong control on streamflow variability.

Improving assessment methods to improve knowledge

Assessing spatial and temporal drought characteristics

Improving the understanding of drought characteristics and drought processes in Central America, as in the rest of the world, is needed to make better decisions within water and disaster management. A very first step needed for this, is knowing the spatial and temporal characteristics of droughts, which until now has not been done at the regional scale in Central America. For this, it is important to know which method and which dataset to use to quantify these characteristics in a reliable way. Many drought indices have been developed and are suitable for different applications and types of climates, and it is important to test the applicability of these indices to characterise droughts (Smakhtin and Hughes, 2004).

In Paper **II** different regional and global meteorological datasets were evaluated. While the results showed that the different datasets could capture important features such as the bimodal distribution of precipitation, they also revealed high uncertainties in terms of monthly precipitation values. The uncertainties were so large, that the differences in calculating the same index with different datasets were larger than using the same dataset to calculate different indices. In order to have an independent indicator of the reliability of the different combinations of drought index and meteorological dataset, we used streamflow data. Even though it is known that the link between droughts in climate and in discharge is complex (Peters *et al.*, 2003; Van Lanen *et al.*, 2013; Van Loon and Laaha, 2015), it was assumed that using meteorological drought indices at monthly time scales is a good indicator, given the strong influence that climate exerts on discharge at these time scales. Other studies have also used precipitation-based drought indices for estimating droughts in other components of the hydrological cycle (Nalbantis and Tsakiris, 2009; Zhai *et al.*, 2010; Liu *et al.*, 2012). Among the evaluated drought indices, one index, the SPEI, accounted for the effects of temperature through evapotranspiration. When calculated within the same dataset (only possible for ERAI and CRU) this index seemed to outperform the rest, which validated the growing criticism to precipitation-based indices (Beguería and Vicente-Serrano, 2013; Teuling *et al.*, 2013). Unlike the SPEI, the SPI, EDI and deciles could be calculated with all the datasets. Results showed that SPI and deciles calculated with CHIRPS and CRN073 gave the best results overall. ERA-Interim and CRU were found to have significant uncertainties. This result highlights the importance of choosing the right dataset to perform hydro-climatic studies.

A method to automate hydrological drought propagation analysis

The drought-propagation analysis performed in the Savegre catchment in Paper **IV** showed a high number of short-duration meteorological droughts. According to Van Lanen *et al.* (2013), this can be expected from catchments in tropical climates. There were also a high number of hydrological droughts with relatively short durations. These occurred as direct response to rainfall deficits, which indicated that hydrological droughts in Savegre were mostly climate dominated. However, there were few events that were not directly linked to specific meteorological droughts and for which the controlling mechanism was more complex. These resulted from insufficient groundwater recharge during the wet season that led to deficits in river discharge during the dry season, when most of it is composed of groundwater discharge. Thus, under these circumstances there were long river-discharge and/or base-flow drought events. This suggests that droughts are also controlled by catchment characteristics and not only by climate in the Savegre catchment. Catchment characteristics have an important role in lag, attenuation, pooling and lengthening, all of which are best represented in composite droughts (Van Loon and Van Lanen, 2012). In Savegre a few composite drought events were identified. In this catchment the high value of the average base-flow index, 0.86, suggests that river discharge has an important groundwater component and that storage is significant in this catchment. Previous studies have found that the complexity in the link between climate and hydrological droughts increases in catchments when groundwater storage becomes more important (Van Loon and Van Lanen, 2012; Haslinger *et al.*, 2014). The important role of storage in attenuating the effects of a severe meteorological drought was evident in the event occurring in 2002. In this event, a relatively long meteorological drought with a high deficit volume was attenuated by storage and, even though it resulted in long river-discharge and base-flow droughts, these did not have significant volume deficits. In agreement, for this event no major impact reports were found. On the other hand, for the composite events occurring in 2000–2001 and 2009, large impacts in agriculture, malnutrition, hydropower production and drinking water supply were reported (ECLAC, 2002; Wolf *et al.*, 2007; Chen *et al.*, 2016). It was found that the accumulation during the rainy season, with respect to normal, could be a good indicator for the occurrence of wet-to-dry season or composite droughts. Under such a scenario, this information could be used to plan for measures to deal with a potentially severe hydrological drought.

The automation algorithm is a step forward towards a more objective drought typology, which is important for its use in decisions within water management.

These results are promising, however, there are some limitations that have to be considered. For groundwater-discharge droughts, the base flow component of river-discharge was used. With this, it is assumed that base flow is mostly groundwater discharge, which has not been validated in this catchment. In addition, this implies that the derived base-flow series is dependent on the river discharge series, and thus it does not represent an independent source of hydrological information (e.g. it contains the same sources of uncertainty than river-discharge data). Finally, the conclusions are limited to the catchment of application and the relatively short period used. The automation algorithm and drought-propagation analysis should be further tested in other tropical catchments with different types of flow regime and if possible, with a longer time series.

A methodology to consistently assess changes in hydrological extremes

In Central America, disasters related to extreme hydro-climatic events have increased (Programa Estado de la Nación, 2016) and according to projected climate scenarios, this situation might worsen in the future (Hidalgo *et al.*, 2013). In addition, urban population has been significantly increasing and this has been done with little if no planning (Programa Estado de la Nación, 2016). There is therefore a high level of pressure on water resources, due to increase of demand of drinking water and electricity (most of which is produced by hydro-power plants), and increased deforestation, urbanisation and soil degradation (Hidalgo *et al.*, 2010). In addition, it should be considered that human activities and hydrological extremes interact and affect each other (Di Baldassarre *et al.*, 2015).

Water management policies need to account, not only for the current spatio-temporal characteristics of floods and droughts, but also for eventual changes in those characteristics through time. But while these policies account for both extremes, studies assessing changes in hydrological extremes usually focus on either floods or droughts individually. In addition, the methods used in these assessments (e.g. POT and annual maximum/minimum discharge series) are usually based on characteristics such as frequency and/or absolute flow value. Other fundamental characteristics, such as length and deficit/surplus volume, are therefore not considered. A consistent methodology to assess changes in both extremes and that provides the aforementioned characteristics, is especially useful in the Anthropocene. During this period, human activity continuously alters the characteristics of both hydrological extremes by e.g. changes in river morphology and water abstraction (Destouni *et al.*, 2013; Hall *et al.*, 2014; Van Loon *et al.*, 2016b).

In Paper **V**, a methodology was proposed to consistently account for changes in both hydrological extremes. The methodology was based on the threshold-level method (Yevjevich, 1967) that, although most commonly used in drought studies, was able to detect important flood events reported in the literature (Zanchettin *et al.*, 2008; Montanari, 2012). The methodology makes the assessment based on the same set of characteristics for both extremes: frequency, duration and deficit/surplus volume, which makes it possible to compare them. The information provided by the consistent methodology can therefore provide useful information for decision making.

The methodology detected the changes in both floods and droughts in the Po River reported in the literature and attributed to the increase in human activity during the last decades (Kottegoda and Natale, 1994; Zanchettin *et al.*, 2008; Di Baldassarre *et al.*, 2009). Thus, this simple methodology has the potential to assess changes in both hydrological extremes and to improve the understanding of how human activities influence floods and droughts.

Some aspects should be considered when applying the methodology in different catchments. The results for the symmetrical threshold-level selection are more comparable than for the impact-focused, but it can come at the expense of compromising part of the information from either of the extremes, since completely symmetrical thresholds might not be applicable at all catchments. A previous assessment should be done before the selection of the threshold-level for each extreme, to ensure the design that provides the most information. Even for the impact-focused version, the selection of the thresholds should be previously evaluated.

The quality and length of the hydrological data available in the Po River basin contrasts with the situation in Central America. Such an assessment would be valuable for the region, but it is difficult to apply due to the data-availability situation. This case study, similar to the Central American studies, highlights the need for allocating more resources into improving the hydro-climatic data network and management to enable reliable characterisation of hydrologic change and hydrologic extremes.

Conclusions

This thesis presents different ways to reduce data-related uncertainties and to improve available methods to study and understand hydro-climatic variability processes. Hydro-climatic data are scarce in Central America, and often limits the quality of hydro-climatic variability studies. A clear example of this was shown by the significant differences observed when calculating the drought indices with different meteorological datasets. Some recommendations were given in order to, as accurately as possible, characterise droughts in the region. Thus, a reliable spatio-temporal characterisation of droughts can be done with these combinations and as a basic, but important step towards risk reduction of droughts in Central America. Data-related uncertainties were also reduced by the development of a new T_{avg} dataset that provides more detailed information than existing datasets. The benefits of having such data were shown and include trend analysis, correlations with climatic phenomena and statistical downscaling of GCM data, including climate projections. All of these applications were done at a spatial resolution that provides information at local and catchment scales. Another way in which data-related uncertainties were reduced was with the proposed methodology for model predictions in ungauged basins based on different parameter and process constraints.

This thesis also contributed to methods and analyses to improve the understanding of drought propagation processes in Central America and elsewhere. Very few studies about drought in the region were found in the literature, even though the socio-economic impacts of droughts are large. One of the main findings can be concluded from the resulting performance of the meteorological drought index based on precipitation and temperature (SPEI), and the drought propagation analysis: it is valuable to consider other variables, not only precipitation, when studying hydrological drought. The SPEI outperformed the other indices when calculated with the same dataset, which suggests that processes related with temperature, through evapotranspiration are important for droughts in the region. In addition, it was found that even though in the Savegre catchment, droughts were strongly climate dominated, catchment characteristics seem to play an important role on the most severe drought events.

The results presented in this thesis are a contribution to improve risk reduction of disasters related to hydro-climatic extremes. Hydrological extremes are changing in the region. It is therefore important to know how these extremes are changing in order to implement proper measures to cope with this change.

Water-management decisions account for both extremes, but most studies treat floods and droughts individually. The new methodology enabled assessment of changes in both extremes in a consistent way, and in addition was able to provide important characteristics, frequency, duration and deficit/surplus volume of both extremes. In addition, the methodology opens opportunities for emerging fields such as socio-hydrological modelling.

The overall results found in this thesis highlight the importance of investing time and resources in making good-quality data available, so that decisions are not based on unreliable information. It also highlights that more effort should be placed on improving the understanding of hydro-climatic variability in the region.

Future research

The work in this thesis has raised research questions that are important to explore. Can the new high-resolution temperature dataset be used to run a hydrological model and produce reliable historical data at different catchments in Central America? Can other types of direct discharge information about be used to reduce uncertainties in hydrological models for ungauged Central American catchments? In addition, knowledge gaps about model-process representation can be filled by assessing the usefulness of different types of additional information on different model structures. Currently, there are no studies that assess the impact of human activities on hydrological extremes. Thus, the region would benefit from such assessments given the increase in human activities and in reported impacts related to hydro-climatic extremes. In addition, drought propagation studies should be done in other catchments in Central America, to improve the understanding of drought-causing mechanisms at the regional level.

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Sammanfattning på svenska (Summary in Swedish)

I Mellanamerika inträffar ofta hydrologiska extremhändelser – översvämningar och torka – kopplade till klimatets variabilitet. Mycket mänsklig verksamhet är beroende av årstidsvariationer i klimat och hydrologi och avvikelser från dessa variationer medför ofta stora konsekvenser. Dessutom lägger usla socioekonomiska förhållanden och brist på planering och förvaltning av regionens vattenresurser hinder i vägen när ländernas regeringar skall hantera de negativa konsekvenserna av sådana naturhändelser. Resultatet blir därför ofta katastrofalt, vilket visar behovet och möjligheterna till förbättringar i riskhantering och katastrofriskreducering. En kritisk del av riskreduceringen är en god förståelse för mekanismerna bakom extremhändelserna, deras rumsliga och tidskarakteristik, och samt möjligheterna att förbättra förutsägelserna av dem. Det är därför viktigt att förstå den normala variabiliteten i klimat och vattenresurser. En nyckelfaktor vid studiet av denna variabilitet är tillgång till långa tidsserier av rumsligt täckande hydrometeorologiska data av bra kvalitet. I Mellanamerika, där det hydro-meteorologiska stationsnätet är glest och där data ofta har kvalitetsproblem, är sådana ideala data tyvärr sällsynta eller finns inte. Dessutom behöver befintliga metoder för hydro-klimatisk analys revideras och/eller förbättras för att identifiera de mest lämpade metoderna för verkligheten i regionen, dess klimat, geografi och situationen vad gäller data.

Det övergripande syftet med denna avhandling har varit att stödja arbetet med riskreducering i Mellanamerika vid hydrologiska extremhändelser som sätts igång av extrema väderhändelser. För att bidra till detta utvecklades metoder för att minska sådana datarelaterade osäkerheter som försvårar studier av variabilitet och förändring av hydrologi och klimat – och genom att förbättra tillgängliga metoder för att studera och förstå de processer som ligger bakom variabiliteten. Dataosäkerheten minskades specifikt för lufttemperatur och simulerad vattenföring. Ett nytt dataset med hög rumslig upplösning utvecklades för lufttemperatur. Detta nya dataset kunde fånga rumsliga mönster på en detaljnivå som hittills inte varit möjlig, vilket möjliggjorde en förbättrad kunskap om klimatets variabilitet i regionen. Tillgängligheten av data för vattenföring är mycket mer begränsad än den för temperatur och nederbörd. Sådana data måste därför huvudsakligen beräknas med hjälp av hydrologiska simuleringsmodeller. Emellertid kräver sådana modeller långa och bra tidsserier av uppmätt vattenföring för att kunna kalibreras med traditionella tekniker, något som begränsar deras användbarhet i Mellanamerika. I avhandlingen föreslås en alternativ kalibreringsmetod för att minska osäkerheten i simulerad vattenföring i avrinningsområden där det saknas vattenföringsdata. Metoden grundar sig på alternativ information för att öka förståelsen av systemets funktionssätt. Expertkunskap om parametervärdens relation sinsemellan, relationen mellan klimat och vattenföring, och upplysningar om lågvattenföring användes som ny information. Metoden var användbar för att minska olika sorters osäkerheter, i synnerhet de som kunde kopplas till icke-konsistenta beskrivningar av grundvattenprocesser. Information om klimatets variabilitet var också användbar för att minska antalet icke-konsistenta representationer. Förhoppningsvis kan resultatet motivera studier av likartat slag i regioner med andra klimat.

Avhandlingen har störst fokus på torka även om den behandlar båda extremerna av vattentillgång (översvämning och torka). Kunskapen om hur torka varierar i tid och rum i Mellanamerika är mycket begränsad, liksom kunskapen om hur torka fortplantar sig från regnbrist via markvattenbrist till uttorkade flodfåror. I avhandlingen utvärderas kombinationer av olika meteorologiska dataset och torkindex för att hitta en möjlig kombination för karakterisering av torka i Mellanamerika. Sådan grundläggande information behövs i regionen, och innan den börjar användas för riskplanering och riskreducering är det viktigt att utvärdera tillämpbarheten hos data och metoder för att säkerställa deras tillförlitlighet. En metodik utvecklades för att kunna studera torkans fortplantning på ett objektivt och automatiserat sätt. Denna metodik har potential att förenkla kommande studier som omfattar många avrinningsområden, samtidiga förlopp och/eller långa tidsserier. Den möjliggör också objektiva jämförelse mellan olika studier. När metodiken användes för ett avrinningsområde i Costa Rica var det möjligt att särskilja olika typer av torka. Torkan var inte bara styrd av klimat utan lagring av vatten i avrinningsområdet visade sig också betydelsefull i synnerhet för sådan torka som fortgick under hela torrperioden. Resultaten i denna analys kan tillämpas såväl i mellanamerikanska som i andra tropiska avrinningsområden.

Slutligen visar avhandlingen hur beslut inom vattenförvaltning och riskhantering bör grundas på konsistent information om förändrade kännetecken hos såväl översvämning som torka för att leda till rätt åtgärder. I Mellanamerika har antalet katastrofer ökat som har sin grund i hydrologiska och klimatextremer. Det finns risk att situationen kan förvärras i ett framtida klimat. En ny metod som hanterar förändringar av båda extremerna på ett konsistentt sätt möjliggjorde en skattning av viktiga kännetecken såsom frekvens, varaktighet och volymer av överskott eller underskott av vatten.

Resultaten i denna avhandling ger bidrag till förståelsen av hydrologiska och klimatextremer genom förbättrade data och analysmetoder som i förlängningen kommer att stödja riskreduceringsarbetet i Mellanamerika.

Resumen extendido (in Spanish)

Centroamérica es considerada una de las regiones más afectadas en el mundo por la ocurrencia de eventos hidro-climáticos extremos. Muchas actividades económicas dependen de las variaciones estacionales del clima y el recurso hídrico, por lo que cambios en esas variaciones traen a menudo grandes consecuencias. Aunado a esto, las condiciones socio-económicas y la falta de planeamiento y del manejo apropiado del recurso hídrico, limitan la habilidad que tienen los gobiernos locales de lidiar con las consecuencias negativas de estas amenazas, las cuales con frecuencia suelen causar desastres. Esto revela que todavía hay mucho por hacer en materia de manejo y reducción de riesgo de desastres. Un aspecto crucial en la reducción del riesgo es entender los mecanismos que causan los eventos extremos, entender sus características espacio-temporales, y mejorar la capacidad para pronosticarlos. Por lo tanto, es necesario entender la variabilidad climática y del recurso hídrico. Para esto es importante tener acceso a una red densa de datos hidro-meteorológicos que consista en series de tiempo largas y de buena calidad. Desafortunadamente, este escenario ideal no es una un realidad en Centroamérica, y los datos disponibles son escasos o no existen del todo, y en general la red de observaciones hidro-meteorológica es poco densa y de baja calidad. Además, los métodos que se usan para hacer estudios hidro-climáticos tienen que ser revisados y/o mejorados, de manera que estos respondan a las necesidades y la realidad climática y geográfica de la región en relación con los datos disponibles.

El trabajo presentado en esta tesis tiene como meta final, contribuir con la reducción del riesgo asociado a los desastres inducidos por la variabilidad hidro-climática en Centroamérica. Esto se buscó primero, tratando de encontrar maneras de reducir las incertidumbres relacionadas con los datos (las cuales interfieren en el estudio y entendimiento de los procesos de variabilidad hidro-climáticos) y segundo, mejorando los métodos que se emplean para hacer estudios de variabilidad hidro-climática. Las incertidumbres de datos se redujeron específicamente para los datos de temperatura y datos simulados de caudal. Para el caso de los datos de temperatura, se desarrolló una nueva base de datos de alta resolución espacial con la cual fue posible identificar patrones espaciales con un nivel de detalle no antes obtenido con las otras bases de datos. Los datos de caudal son mucho más difíciles de obtener que los de temperatura y precipitación, por lo que es común que estos tengan que ser simulados con modelos hidrológicos. Sin embargo, los métodos tradicionales de calibración requieren de observaciones de caudal que tengan buena calidad y que cubran periodos largos, por lo que estos métodos no son útiles para ser aplicados en regiones como Centroamérica.

En esta tesis, se desarrolló una alternativa a los métodos tradicionales de calibración para reducir las incertidumbres en el modelado hidrológico de cuencas no aforadas. El método se basa en usar otros tipos de información, en lugar de datos observados de caudal, para entender mejor cómo funciona el sistema. Los otros tipos de información se basaron en el conocimiento experto sobre las relaciones entre los parámetros del modelo, y de la relación clima-caudal.

También se utilizó información directa sobre características del caudal. Con el método fue posible reducir significativamente las incertidumbres, especialmente aquellas relacionadas con representaciones inconsistentes de las aguas subterráneas. El tipo de información adicional que más rechazó parámetros, fue la información basada en relaciones entre parámetros, pero las representaciones que más rechazaron representaciones inconsistentes fue la información directa de las características del caudal. Sin embargo, la información sobre la relación clima-caudal pudo rechazar representaciones inconsistentes que los otros tipos de información no pudieron rechazar. Se espera que estos resultados motiven el desarrollo de enfoques similares en regiones con otros tipos de clima.

Este trabajo se enfocó especialmente en las sequías. En Centroamérica, el conocimiento sobre las características espacio-temporales de las sequías, así como sus procesos de propagación, es limitado. En esta tesis, se hizo una evaluación de diferentes bases de datos e índices de sequía, para encontrar cuál combinación es la más apropiada para la caracterización de las sequías. La información obtenida de dicha caracterización, aunque básica, es necesaria en la región, pero es importante evaluar la aplicabilidad de las bases de datos y de los métodos usados, antes de que esta información sea usada en la toma de decisiones. Además, en esta tesis se desarrolló un método para analizar la propagación de las sequías de una forma objetiva y automatizada. Esta metodología simplifica el trabajo para estudios que traten con series de tiempo largas y/o con muchas cuencas a la vez y además permite que los estudios se puedan comparar objetivamente. Se hizo un análisis de propagación de sequía en una cuenca en Costa Rica. Con este análisis se encontró que aunque las sequías están mayormente moduladas por el clima, las características de la cuenca también juegan un papel importante. Estos resultados son un paso importante hacia una mejor comprensión de los patrones y mecanismos detrás de las sequías en las cuencas de Centroamérica.

Finalmente, la toma de decisiones para el manejo del recurso hídrico y de desastres en la región necesita de información consistente acerca de los cambios que se han presentado en las características de las sequías e inundaciones a través del tiempo, si se quiere implementar medidas apropiadas. En Centroamérica, la ocurrencia de desastres asociados a eventos hidro-climáticos extremos se ha incrementado, y se estima que esta situación va a empeorar en el futuro. En esta tesis, se propuso un método para evaluar, de una manera consistente, los cambios en sequías e inundaciones. Con el método fue posible obtener características importantes como la frecuencia, la duración y el volumen de déficit/superávit.

Los resultados presentados en esta tesis contribuyen a mejorar la reducción del riesgo de desastres asociados a eventos hidro-climáticos extremos en Centroamérica, al mejorar los datos y los análisis hidro-climáticos.

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