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Flood Hazard Assessment in Data-Scarce Basins

Use of alternative data and modelling techniques

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Abstract

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Flooding is of great concern world-wide, causing damage to infrastructure, property and loss of life. Low-income countries, in particular, can be negatively affected by flood events due to their inherent vulnerabilities. Moreover, data to perform studies for flood risk management in low-income regions are often scarce or lacking sufficient quality.

This thesis proposes new methodologies and explores the use of unconventional sources of information in flood hazard assessment in areas where the quantity or sufficient quality of traditional hydrometrical data are lacking.

One method was developed to account for errors in spatially averaged rainfall, from a sparse rain-gauge network, used as input to a rainfall-runoff model. A spatially-averaged and event-dependent rainfall depth multiplier led to improvements of the hydrographs at calibration. And by using a distribution of the multiplier, identified from previous events in the catchment, improvement in predictions could also be obtained.

A second method explored the possibility of reproducing an unmeasured extreme flood event using a combination of models, post-event data, precipitation and an uncertainty-analysis framework. This combination allowed the identification of likelihood-associated parameter sets from which the flood hazard map for the extreme event could be obtained.

A third and fourth study made at the regional scale explored the value of catchment similarities, and the effects of climate on the hydrological response of catchments.

Flood frequency curves were estimated for 36 basins, assumed ungauged, using regional information of short flow records, and local information about the frequency of the storm. In the second regional study, hydro-climatic information provided great value to constrain predictions of series of daily flow from a hydrological model.

Previously described methods, used in combination with unconventional information within an uncertainty analysis, proven to be useful for flood hazard assessment at basins with data limitations. The explored data included: post-event measurements of an extreme flood event, hydro-climate regional information and local precipitation data. The methods presented in this thesis are expected to support development of hydrological studies underpinning flood-risk reduction in data-poor areas.

Keywords: Central America, floods, data scarcity, data quality, uncertainty analysis, regionalisation, flood frequency analysis, GLUE, hydraulic modelling, rainfall-runoff modeling, TOPMODEL, LISFLOOD-FP, GRADEX, index-flood, Muskingum-Cunge-Todini flow routing

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Spanish abstract

Evaluación de riesgo por inundación en cuencas con datos limitados. Uso de datos y técnicas de modelación alternativos

Las inundaciones ocasionan daños a la infraestructura, propiedad y pérdida de vidas a nivel mundial. Los países en desarrollo son los más vulnerables a inundaciones, la calidad y cantidad de datos hidro-climatológicos disponibles en los mismos dificulta el desarrollo de estudios para la evaluación de riesgo a esta amenaza. Esta tesis propone métodos en la que se hace uso de fuentes de información no-convencionales para la evaluación de riesgo por inundación en regiones con datos escasos o limitados.

Un método considera el error asociado a la precipitación promedio sobre cuencas en modelos lluvia-escorrentía como un factor multiplicador del histograma del evento. El uso de la precipitación promedio junto con una distribución probabilística del factor multiplicador como datos de entrada a un modelo de lluvia-escorrentía mejoraron los hidrogramas durante los periodos de calibración y predicción.

Un segundo método exploró la posibilidad de reproducir un evento extremo de inundación usando una combinación de modelos hidrológicos e hidráulico, un análisis de incertidumbre, datos hidrométricos recopilados después del evento y datos de precipitación registrados durante-el-evento. Dicha combinación permitió la identificación de los parámetros de los modelos y la elaboración un mapa de amenaza por inundaciones para dicho evento.

Adicionalmente, se estimaron curvas de frecuencia de inundaciones para 36 cuencas, asumidas no aforadas, mediante un método de regionalización que usa registros de caudal de corta duración disponibles en la región. Dichas curvas fueron extendidas haciendo uso de información local sobre la frecuencia de las tormentas. Se encontró que la información hidro-climatológica tiene un gran valor para reducir el rango de incertidumbre de las simulaciones de caudal diaria de un modelo hidrológico.

Los métodos anteriores se usaron en combinación con información no-convencional dentro de un análisis de incertidumbre y han probado su utilidad para la evaluación de riesgo por inundaciones en cuencas con registros escasos o limitados. Los datos utilizados en esta tesis incluyen datos hidrométricos recopilados pasado el evento, registros hidro-climatológicos regionales y precipitación local. Se espera que los métodos presentados aquí contribuyan al desarrollo de estudios hidrológicos importantes para la reducción del riesgo por inundaciones en regiones con déficit de registros hidro-climatológicos.

Palabras claves: Central América, inundaciones, escasez de datos, calidad de los datos, análisis de incertidumbre, regionalización, análisis de frequencia de inundación, GLUE, modelación hidraulica, modelo de lluvia-escorrentía, TOPMODEL, LISFLOOD-FP, GRADEX, índice de inundación, Muskingum-Cunge-Todini rutina de propagación de flujo.

Swedish abstract

Riskbedömning av översvämning i avrinningsområden med dålig datatillgång. Användning av alternativa data och modelleringsverktyg

Extremt höga vattenflöden ställer till stora problem i hela världen. De skadar infrastruktur och egendom och orsakar död. Framför allt kan låg- och medelinkomstländer vara väldigt sårbara för extrema flöden. I dessa länder saknas dessutom ofta data som behövs för att kunna bedöma översvämningsrisker, eller så finns bara data av dålig kvalitet.

Denna avhandling föreslår nya metoder som använder okonventionella informationskällor vid bedömning av översvämningsrisker i områden där traditionella hydrologiska data saknas eller har otillräcklig kvalitet.

En metod utvecklades för att ta hänsyn till fel i rumslig medelnederbörd beräknad från ett glest nät av nederbördsmätare att användas som indata i en nederbörds-avrinningsmodell. Användning av en multiplikator för medelvärdesbildad nederbörd, i tid och rum, för enskilda högflödestillfällen ledde till förbättrad modellkalibrering. Genom att använda multiplikatorfördelningar, identifierade från tidigare högflödestillfällen i avrinningsområdet, kunde också prognoser förbättras.

En andra metod använde sig av möjligheten att reproducera ett extremt högflöde inom ramen för en osäkerhetsanalys med hjälp av en kombination av modeller, nederbördsdata och data som uppmätts i efterhand. Denna kombination gjorde det möjligt att identifiera parametervärdesuppsättningar med hophörande sannolikheter ur vilka det gick att erhålla en översvämningskarta för det höga flödet.

En tredje och fjärde studie i regional skala utforskade värdet av likheter mellan avrinningsområden och hur områdenas hydrologiska gensvar beror av klimatet.

Kurvan för kumulativa högflödesfrekvenser (flood frequency curve, FFC) kunde skattas med hjälp av lokal nederbördsinformation och regional information om korta tidsserier av vattenföring från 36 avrinningsområden som antogs sakna vattenföringsdata. I den andra regionala studien visade sig hydroklimatisk information av värde för att avgränsa godtagbara prognoser för daglig vattenföring från en hydrologisk modell.

Tidigare beskrivna metoder, använda tillsammans med okonventionell information inom ramen för en osäkerhetsanalys, visade sig vara användbara för att bedöma översvämningsrisker i avrinningsområden med databegränsningar. Bland utforskade data fanns: mätningar i efterhand av ett extremt högflöde, hydroklimatisk regional information och lokala nederbördsmätningar. Metoderna i denna avhandling förväntas kunna stödja utvecklingen av hydrologiska studier av höga flöden och översvämningar i områden med bristande datatillgång.

Nyckelord: Mellanamerika, högflöde, datakvalitet, osäkerhetsanalys, regionalisering, frekvensanalys av högflöden, GLUE, hydraulisk modellering, nederbörds-avrinningsmodeller, TOPMODEL, LISFLOOD-FP, GRADEX, indexflöde, Muskingum-Cunge-Todini flödessvarstid

To all that is.

List of Papers

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

- I **Fuentes-Andino, D.**, Beven, K., Kauffeldt, A., Xu, C.-Y., Halldin, S. and Di Baldassarre, G.: Event and model dependent rainfall adjustments to improve discharge predictions. Hydrol. Sci. J., 62(2), 232–245, doi:10.1080/02626667.2016.1183775, 2017a.
- II **Fuentes-Andino, D.**, Beven, K., Halldin, S., Xu, C.-Y., Reynolds, J.-E. and Di Baldassarre, G.: Reproducing an extreme flood with uncertain post-event information. Hydrol. Earth Syst. Sci. Discuss., 1–35, doi:10.5194/hess-2016-496, 2016.
- III **Fuentes-Andino, D.**, Beven, K., Quesada, B., Halldin, S., Xu, C.-Y. and Di Baldassarre, G.: Regionalised flood frequency analysis: the index-flood and the GRADEX methods combination. Manuscript, 2017b.
- IV Quesada-Montano, B., Westerberg, I., **Fuentes-Andino, D.**, Hidalgo, H. and Halldin, S.: Can climate variability information constrain a hydrological model for an ungauged Costa Rican catchment? Hydrol. Process., In review., 2016.

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In Paper **I,** I was responsible for the formulation of the hypothesis with the support of Keith Beven. I performed the analyses and was main responsible for writing of the manuscript, Anna Kauffeldt helped with the structure to the paper. All co-authors contributed with advice and in the writing of the paper. In Paper **II,** the hypothesis was formulated in discussions with the co-authors. I was responsible for executing the analyses, and for writing the paper with the help of the co-authors. I was also responsible for the hypothesis, the analysis and the writing of Paper **III**, where all co-authors contributed with ideas and added to the paper. I contributed to Paper **IV** with suggestions on approach and coding of the reliability- and precision-evaluation techniques, also assisted with discussions of the uncertainty analysis and results, and in the writing of the paper.

Contents

Abbreviations

CLLJ	Caribbean low-level-jet index
DBM	Data-based mechanism modelling
FRMS	Flood risk management system
FFA	Flood-frequency analysis
FFC	Flood-frequency curve
ERRM	Event-based rainfall-runoff model
GEV	Generalised extreme value distribution
GLUE	The generalised likelihood uncertainty estimation
GNSS	Global Navigation Satellite System
GRADEX	Gradient of extreme values
MCT	Muskingum-Cunge-Todini flow routing
NSE	Nash-Sutcliffe model efficiency coefficient
masl	Metres above sea level
RE	Relative error
RRM	Rainfall-Runoff Model
TOPMODEL	Topographically-based model
WMO	World meteorological organisation

Introduction

Flooding causes increased mortality, morbidity, population displacement and significant economic losses world-wide (Doocy et al., 2013). In the last few decades, fifty percent of all natural-disaster victims have been due to floods (Jonkman, 2005). The impact of flooding is especially severe in low-income countries due to their economic, social, political and cultural vulnerability (Alcántara-Ayala, 2002; Cardona, 2004). The consequences in such countries are expected to be aggravated due to climate change (Charvériat, 2000).

Central America is one of the regions that are most at risk of flooding due to the threat from hurricanes (Alvarado and Alfaro, 2003; Strobl, 2009), a threat that is exasperated by societal vulnerabilities (Pielke et al., 2003). In 1998, the damage caused by Hurricane Mitch accounted for 11,000 casualties in the region, and an estimated 2.7 million people losing their homes and damages amounted to a loss of 6 billion USD (McCown et al., 1999).

The prevention and mitigation of floods require flood hazard assessment as part of a flood-risk-management system (FRMS) (Schanze, 2006; Yan et al., 2017). Traditionally, a FRMS relies on the use of local long discharge records at a gauged site or from different sites, through regionalisation methods, to make a statistical analysis of the frequency of floods (Blöschl et al., 2013). However, such approaches are limited in the region given the quality and availability of data. Economic difficulties have led to flood-risk-mitigation measures being relegated to a secondary position in the political agenda of many Central American nations. This is one of the reasons for the lack of data necessary for flood-hazard assessments, while the data that do exist are often sparse and/or of poor quality (Balairon Perez et al., 2004; Flambard, 2003; Guerrero et al., 2012; Soto, 2015; Westerberg, 2011). The Central American region has a high spatial and temporal variability of rainfall (Amador, 2008; Maldonado, 2016) thus the problem with the lack and quality of data, common in other low-income countries (Meigh et al., 1993), has a particularly severe effect in this region.

Flood-hazard assessments require the use of models designed to be as realistic as possible in their representation of the real system. But limited knowledge about the system (epistemic uncertainty) and data incommensurability issues (Beven, 2016) mean that models will never be entirely free from errors. In addition, observational data, for input and evaluation, which are the foundation for the setting-up and well-functioning of the models, are usually insufficient and associated with errors (Sivapalan, 2003).

Given the different sources and causes of uncertainties, a joint analysis that considers possible uncertainties in both models and data is necessary to draw useful conclusions (Kirchner, 2006; Kuczera et al., 2010). Such techniques consider the uncertainty in model structure, parameters and observational data by allowing them to interact with each other. A likelihood is assigned to each combination depending on how well it compares with calibration data.

Uncertainties inherent in the modelling process coming from the model and observational data are propagated to the flood predictions, such as through a flood hazard map (e.g. Aronica et al., 2012; Di Baldassarre et al., 2010; Romanowicz and Beven, 1998), in the form of a predictive likelihood. The result from the uncertainty analysis is important since it can affect the decision-making process (Beven and Smith, 2015). Stakeholders must therefore be prepared to make decisions under these unavoidably uncertain conditions (e.g. Beven et al., 2015).

The predictive uncertainty of models increases greatly when there are large uncertainties coming from the quality or scarcity of data (Rougier and Beven, 2013). These uncertainties depend highly on the assumptions about each of the sources of uncertainty in the absence of observations for calibration (Beven and Smith, 2015). In order to reduce predictive uncertainty at ungauged basins, there is a need for additional novel data, a better understanding of the processes, and an understanding of the connections of the climate and landscape heterogeneities and how they affect the hydrological processes across scales (Blöschl et al., 2013; Sivapalan, 2003). Flood hazard assessment under high uncertainties associated with data limitations common in developing nations remains a challenge.

Aim of this thesis

The general aim of this thesis is to develop methodologies that contribute to flood hazard assessment at basins with data limitations. The general aim can be broken down into two specific objectives:

I. Develop techniques for flood prediction under conditions of data limitation as i.e. scarcity and lack of high quality data (Papers **I**, **II** and **III**).

II. Explore the usefulness of unconventional sources of information for flood prediction (Papers **II**, **III** and **IV**).

Background

Flood risk

Floods are defined as a temporary covering of land by water outside its normal confines (FLOODsite-Consortium, 2005). While floods are a natural phenomenon, there is nevertheless a dynamic interaction and feedback loop between floods and human activities (Di Baldassarre et al., 2013). The negative consequences of flooding lead to a need to understand the frequency and character of the flood threat (Schanze, 2006). It is thus important to examine the magnitude and potential damage from a flood for a given return period.

The selection of a given return period depends on the risk a society would accept, and it is usually made as result of a cost-benefit analysis (Rosbjerg et al., 2013). The risk for flooding is estimated as the probability of occurrence of a flood of a given magnitude (flood hazard) and the assessment of the consequences due to that flood hazard (Merz et al., 2007). The assessment of the exposure to the hazard requires the spatial mapping of variables that describe the severity of the flood, which is done through a flood hazard map (Brown and Damery, 2002). Areas for improvement in the flood hazard map include the incorporation of an uncertainty analysis, different variables indicating the severity of the threat, different sources of flooding such as reservoirs and a standardising the methods for making such maps (Brown and Damery, 2002; Merz et al., 2007).

Modelling techniques for flood prediction

Rainfall-runoff models (RRM) use climatic inputs and some mathematical formulation that describes the landscape response to these inputs to estimate the hydrograph at a catchment outlet (Beven, 2012; Jakeman and Hornberger, 1993). Flood hazard assessment use RRM to predict a discharge series (Paper **IV**). RRM can also be used in a continuous simulation method for flood-frequency analysis (Blazkova and Beven, 2009), or in a model cascade with hydraulic models to propagate the flood wave (Paper **II**). Differences in perception and in the mathematical formulation of an RRM result in different model structures, which are useful for different purposes and in different regions (Beven, 2012). An RRM can be based on data-driven procedures in which only the relationship between observed rainfall and runoff is analysed, such as in artificial-neural-network (ANN) models, or they can be based on a physical understanding and interpretation of the processes. In the latter case there are simple lumped, distributed and semi-distributed models depending on how localised a representation one makes of the model variables and the respective outputs. Commonly used modelling tools for lumped, distributed and semi-distributed models are HBV (Bergström, 1976 and used in Paper **IV**), MIKE SHE and TOPMODEL (Beven and Kirkby, 1979 and used in Paper **I** and **II**), respectively. The over-parameterisation of fully distributed models limits their applicability due to data requirements for both input and evaluation. It is necessary to develop distributed models on a detailed scale in order to improve the understanding of the processes, which will later benefit the predictions at ungauged basins, while much simpler models are advantageous for practical application such as real-time prediction and uncertainty assessment when data is limited (Beven, 2012).

Flow routing uses mathematical relationships to determine the flow value or hydrograph at a downstream river location by knowing the upstream inflow and some characteristics of the river stretch. Flow routing thereby propagates a flood wave from upstream to downstream, which can be used to predict ahead of time the peak of the flood, which is needed for forecasting, or to spatially characterise the development of the flood wave in a floodplain useful for both flood forecasting and flood hazard assessment. As with all models, flow routings are a simplification of the real system, and are bound by various assumptions related to the flow conditions, such as flow incompressibility, uniformity and steadiness (Toombes and Chanson, 2011). Flow routing can be modelled on an empirical relationship between input and output flow based on observations, such as the Manning equation, or it can be based on an understanding of the physical processes, for instance on the conservation of mass (hydrological routing, e.g. Muskingum-Cunge-Todini [Todini, 2007] used in Paper **II**) and on the conservation of mass and momentum (hydraulic routing). There are many examples of the latter, all based on different simplification of the partial differential Navier-Stokes equations (Novak et al., 2010). The LISFLOOD-FP hydraulic package (Bates and De Roo, 2000) used in Paper **II**, provides different versions of these simplifications. The choice of a flow-routing method depends on the type of flood, the accuracy required, the type and availability of data and the information desired (USCE, 1994).

Results from flow-routing methods are associated with errors from observed discharge, often large because of the lack of representativeness of the rating curve from where the values are estimated (Candela et al., 2007; Domeneghetti et al., 2012; Guerrero et al., 2012) and particularly for high floods when curves must generally be extrapolated (Di Baldassarre and Claps, 2011). These errors might be avoided by the use of data-based-mechanism

(DBM) modelling (Young, 1998) where flow routing can be done through the use of water level instead of discharge (Young et al., 2009).

Flood-frequency analysis (FFA) is based on information on series of past peak flow in order to supply a useful prediction of the frequency of flooding. The return period of a peak flow of a given magnitude is the expected average length of time between the occurrences. The probability of exceedance is inversely proportional to the return period. Statistical methods are used to obtain the flood-frequency curve (FFC), i.e. the plotting of the flow values against either probability of exceedance, non-exceedance or return period (Reiss and Thomas, 2007).

All methods for FFA involve three main choices: data, statistical model and parameter-estimation procedure (Kidson and Richards, 2005). The first deals with the selection of the peak series to be used in the analysis, e.g. partial duration or annual maximum series. The second deals with the theoretical distribution used to fit the observed peak series e.g. the generalised extreme value distribution (GEV) used in Paper **III**, and the third deals with estimation of parameters of the chosen theoretical distribution, e.g. least squares, method of moments (MOM) and the probability-weighted moments (PWM) used in Paper **III**.

Each of the previous steps are associated with uncertainties due to a lack of knowledge of the processes (Merz and Thieken, 2005). An important source of uncertainty is the limited information in the data. For example, the estimated FFC might be associated with large errors in the tails due to the limited number of data used for its creation (Stedinger et al., 1992). There is also a possibility that some of the values at the extreme end of the FFC have a recurrence lower than the length of the flow record (Guillot, 1993).

Another uncertainty arises from the possible violation of the basic assumption of traditional FFA methods, i.e. that the hydrological data are stationary, independent and identically distributed over time. However, in the past decades this stationarity assumption has been severely challenged because global climate change (Beguería et al., 2011) and/or when large-scale human activities (Magilligan and Nislow, 2005) have altered the statistical characteristics of hydrological processes (Xiong et al., 2015). In the presence of nonstationarity, some researchers use time-varying moments of distribution (Milly et al., 2015; Stedinger and Griffis, 2011).

Uncertainty analysis for modelling

Modelling systems are designed to be as realistic as possible representations of the hydrological system, but there is always a lack of knowledge of the processes involved in the modelling systems, i.e. epistemic uncertainty (Beven, 2016). There is also a difference in spatial and temporal scale between the variables that the model represent and the observed ones, this is known as an incommensurability error (Beven, 2003). Ideally, model-based predictions should be verifiable through observation, which however are also associated with uncertainties (Beven, 2009). The inclusion of disinformative data, i.e. data that can be misleading in the evaluation process, might lead to erroneous conclusions about the system response (Beven and Smith, 2015; Beven and Westerberg, 2011). Also, unusual or more extreme events might be poorly predicted due to the lack of enough representative data for calibration (Beven, 2009).

Modelling processes are therefore associated with uncertainties stemming from model structure, model parameters and observational data in addition to the computational constraints and effects of the sources of uncertainty in model calibration. In an uncertainty analysis, different sources of uncertainty interact among each other normally in a complex way. This leads to the equifinality thesis (Beven, 2006) where not only one but many parameter sets and model structures representative of the system can provide acceptable simulations of the available observations (behavioural models). Each behavioural model can be associated with a likelihood that reflects how well the predictions of that model realisation compares with observations. In a formal uncertainty-analysis technique such as the Bayesian statistical approach, a likelihood function depends on a structure assigned to the errors. The structure of the error is formulated based on some assumption of their distribution, e.g. form of the distribution, stationarity, heteroscedasticity, correlation. If the assumptions about the error prove correct, the prediction of a new observation can be associated to a probability (e.g. Cheng et al., 2014; Li et al., 2011, 2013; Renard et al., 2008). However, errors from calibration might be different from those at prediction because of epistemic uncertainty, thus the assumption of stationarity in the model error is debatable (Beven and Smith, 2015).

The generalised likelihood uncertainty estimation (GLUE) method (Beven, 2009; Beven and Binley, 1992) is an informal uncertainty-estimation technique where strong assumptions about the structure of the errors are circumvented. GLUE allows for complex interactions between parameters, implicitly including variance and co-variance forms. The complex interactions are thereby implicitly contained in the resulting ensemble of behavioural simulations.

Within GLUE a parameter set is evaluated as behavioural or not by explicitly choosing a model evaluation criteria. These choices are important since they affect the confidence limits of the model-predicted variable and should be made by the modeller based on the type of observational data available. For example, the Nash–Sutcliffe model efficiency coefficient can be used where all simulations above a defined efficiency are considered behavioural (used in Paper **I**); or the definition of limits of acceptability that considers the uncertainty in the observed data, where simulations within these limits are considered behavioural (e.g. Blazkova and Beven, 2009; Liu et al., 2009; Paper **II** and **IV**). The likelihood then is estimated based on the evaluation criteria used, and it is required to be zero for models considered unacceptable or non-behavioural, but should increase with increasing levels of performance, and should scale to sum to unity over all the models retained as behavioural (Beven and Binley, 1992). Application of the GLUE can result in a failure of the model if no parameter set is found acceptable. In this case we should understand modelling as a learning process, since it requires that the characteristics of the failure should be examined and some better model structure or more informative data be developed. The GLUE method assumes that the characteristics of the errors in prediction will be similar to the ones obtained in calibration (Beven and Smith, 2015).

Predictions for flood hazard assessment should be done within a framework that takes the main sources of uncertainty into account. It is recommended that the process for defining assumptions about the uncertainties is carried out within established guidelines in which the stakeholders participate in the decisions on how to treat the different sources of uncertainty so as to improve the way decisions regarding flood mitigation are made (Beven et al., 2014).

Flood prediction in ungauged basins

Many catchments lack discharge measurements, the International Association of Hydrological Sciences (IAHS) established the “Decade on Predictions in Ungauged Basins (PUB): 2003–2012” with the goal to improve hydrological predictions in ungauged basins (Sivapalan et al., 2003). They define ungauged basin as the one for which records of hydrological variables of interest are limited in quantity or quality, in both space and temporal scale, so that they cannot properly support practical applications. To make predictions for any basin it is necessary to have a model that describes the processes, a set of parameters that represents the properties of the landscape and boundary and initial conditions which drive that response. These components are either unknown, partly known or associated with large errors, particularly in ungauged basins. During the PUB decade, many methods were developed to predict discharge in catchments lacking observations (Merz and Blöschl, 2004; Parajka et al., 2007; Young, 2006). Achievements from PUB and remaining challenges in the field of runoff predictions in ungauged basins are reviewed by Hrachowitz et al. (2013).

The different approaches to solving the prediction problems in ungauged basins include the application of fundamental theories through process understanding, inference from gauged catchments through regionalisation and the addition of novel data, all of which are conditioned to observations at gauged sites (Sivapalan et al., 2003). These inferences from gauged to ungauged catchments are associated with large errors because of a lack of understanding of the processes, because of the space-time heterogeneity of a landscape and because the model results for an ungauged basin cannot be conditioned on observations (Sivapalan, 2003). It is therefore necessary to account for uncertainties in predictions regarding ungauged basins. Approaches should be developed to evaluate the predictive limits at gauged basins before using them in ungauged basins (Hrachowitz et al., 2013). This will also enable an assessment of how much the uncertainty can be reduced by added data.

Process understanding through the use of rainfall-driven models is an alternative for an ungauged basin. Under data limitations, the predictive uncertainty from such models depends greatly on the uncertainties in the model structure and available input data. Thus, to compensate the lack of data for calibration, ideally the model structure should be as similar as possible in the representation of the hydrological processes which implies the use of detailed data as input. In such models, the model parameters are expected to be physical based and can be estimated *a-priori* from the characteristics of the ungauged catchments (Parajka et al., 2013).

An understanding of the climate and landscape connections and their effect on hydrological processes across scales help to make inference from gauged catchments. Regionalisation methods take advantage of similarities in the hydrological response of catchments for the transfer of information from a gauged to an ungauged catchments. Regionalisation methods can be used to obtain the parameters of an RRM and within flood prediction to estimate the characteristics of the flood-frequency curve. In the former case, the model structures and behavioural parameters previously tested in gauged catchments with similar climate and catchment characteristic can be transferred to the ungauged ones (Blöschl, 2006). Regionalisation methods for flood-frequency analysis use a number of catchment characteristics to make predictions for the ungauged basin which include (i) spatial-proximity methods based on geographical distance; (ii) physical-similarity methods based on catchment characteristics; (iii) methods combining spatial proximity and physical similarity; (iv) Kriging interpolation, and (v) regression-based methods

(Griffis and Stedinger, 2007; Hrachowitz et al., 2013; Vogel, 2005; Xu, 1999, 2003). An example of physical similarity methods is the index-flood method (Dalrymple, 1960; Institute of Hydrology, 1999) used in Paper **III**.

Predictions for ungauged basins can be constrained through the use of alternative data as post-event hydrometric measurements (Borga et al., 2008) and information of catchment characteristics that describe the dynamic behaviour of the basin, known as signatures (Wagener and Montanari, 2011).

Signatures can be obtained from discharge or other data in the region of interest (e.g. Westerberg and McMillan, 2015) or by including data, other than long flow records, which is available in the ungauged basin and can be used to constrain or improve predictions (e.g. Montanari and Toth, 2007). Such signatures can then be compared with the model predictions in the ungauged basin in order to reject those that do not behave according to the characteristics of the signature. Hydro-climatic information in the region, for example, can help constrain model outputs from an RRM (Paper **IV**) and the local information of the frequency of storms can be used as a signature of the shape of the flood-frequency curve for catchments that follow the assumptions of the gradient of extreme values (GRADEX) theory (Guillot and Duband, 1967) used in Paper **III**.

Study area

This thesis includes different catchments located in the central region between the American continents. Focus was placed on catchments from Central America but also a regional study including the surrounding areas of Mexico, the Caribbean and the northern part of South America (within 3°– 23° N and 101°– 65° W domain) was part of this study (Fig. 1). One catchment in China with characteristics similar to those of the study region and where data of extreme flood events were available was used in Paper **I** to test an Event-based Rainfall-Runoff Model (ERRM) set-up.

Paper **I** studied a basin located in Zhejiang province, south-eastern China with an area of 259 km^2, a mean annual precipitation of about 2000 mm and an elevation ranging from 80 to 975 masl. Paper **II** studied 13 km of river length in the Tegucigalpa floodplain and three floodplain-upstream sub-catchments with areas varying from 71 to 448 km^2, a mean annual precipitation of about 1100 mm and an elevation ranging from 900 to 2300 masl. Paper **III** studied 60 basins in the central region between the American continents, with areas varying in size from 47 to 4772 km^2, mean annual precipitations varying from 740 to 5340 mm and elevations varying from zero to 2470 masl. Paper **IV** used regional information from 10 catchments in Central America, where the areas varied from to 148 to 5527 km^2 and mean annual precipitations from 252 to 4190 mm.

Precipitation variability in the Central American region is mainly the consequence of the latitudinal migration of the ITCZ, easterly winds, hurricanes, the oscillation of the sea-surface temperatures in the surrounding oceans, and local topography (Alfaro, 2002; Amador et al., 2006; Portig, 1965). Topography alone is an influential factor for rainfall spatial variability at mountainous areas (Buytaert et al., 2006).The interaction of topography with all the above mentioned aspects of climate variability leads to a high spatial variability of rainfall in the region (e.g. Westerberg et al., 2010). Temporal variability at the short, intra-annual and inter-annual time scales is also high and affects the hydrological processes in the region (Peña and Douglas, 2002). For example, the flood frequency has been associated with the inter-annual variability of the El Niño Southern Oscillation (ENSO) phenomenon in the region (Waylen and Laporte, 1999) and in other places in the world (Rosbjerg et al., 2013). And the intra-annual cycle of the discharge follows the bimodal distribution of the precipitation in the Pacific side of the region (Alfaro, 2002; Paper **IV**). Thus, the links between climate and catchment dynamics promises to be worth exploring for prediction in ungauged basins in the region.

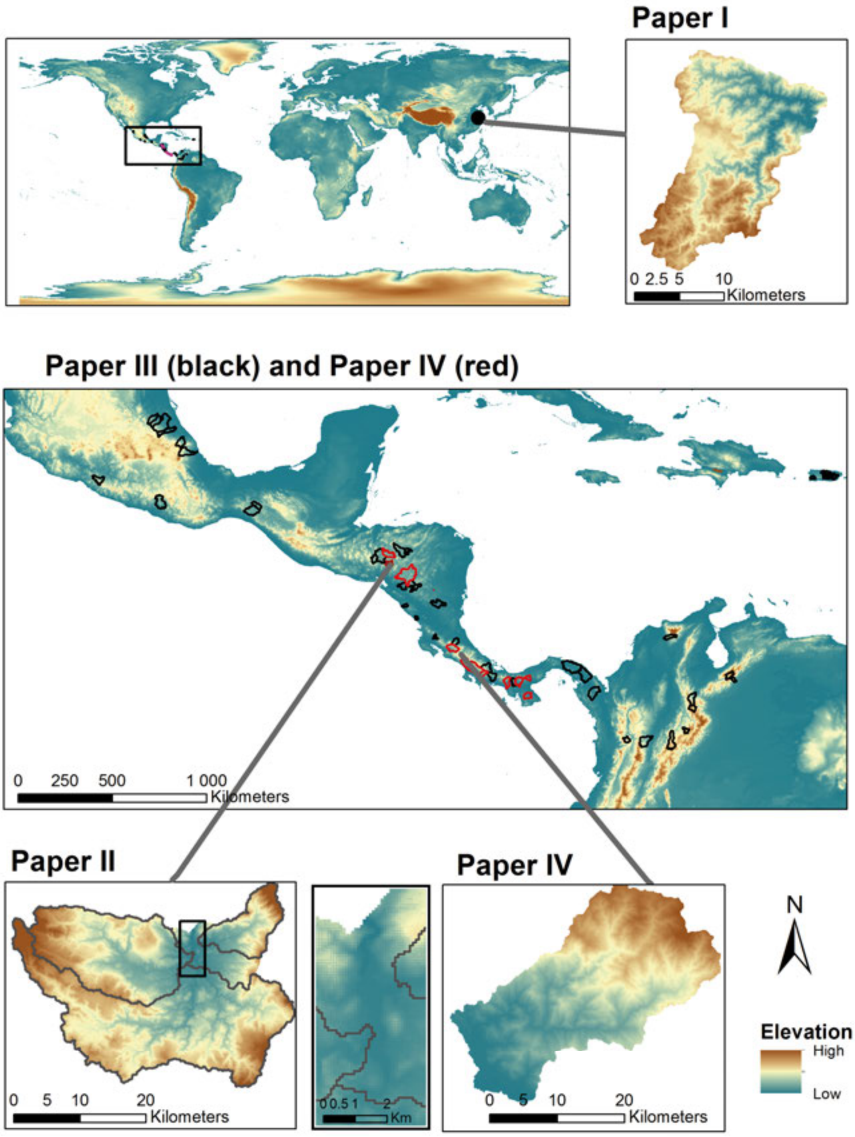

Figure 1. Basins used in the analysis of the included papers; in China, Honduras and Costa Rica at the local scale (Paper **I**, **II** and **IV** respectively) and in Central America and the surrounding area at the regional scale (Paper **III** and **IV**).

Characterisation of the high spatiotemporal variability of the climate in the region requires frequent sampling and a dense gauging network (Hastenrath, 1967; Westerberg et al., 2010). Furthermore, the sediment load and erosion common in steep terrain lead to non-stationary river beds and therefore cause errors in the rating curve from which discharge is derived (Guerrero et al., 2012; Westerberg, 2011). Notwithstanding the need for denser and more frequent measurements in the gauge network in the area, various studies have pointed out the problem of scarcity and lack of quality of the hydro-meteorological data in the region (Balairon Perez et al., 2004; Flambard, 2003; Westerberg, 2011).

Different institutions within each country in Central America are in charge of collecting hydro-meteorological data, and the efforts required to obtain the data are subject to various requirements and bureaucratic rules in the institutions (Flambard, 2003). Some effort has been made to make regional or global data available, as such data are useful for gaining a better understanding of the hydrological pattern at the regional scale (Sivapalan, 2003). Gridded precipitation data for the region are available from the CRN073 data set (Magaña et al., 1999) and the TRMM data set (Huffman et al., 2007), where the latter has important inconsistencies with local precipitation data (Westerberg et al., 2014). The spatial resolution of such a data set might be low in comparison with the precipitation variability in the area, which can lead to inconsistencies in event and long-term runoff coefficients (Westerberg et al., 2014; Paper **III**).

A total of 155 stations with daily discharge data were available from the World Meteorological Organization (WMO) through the Global Runoff Data Centre (GRDC, 2016) within the domain of Paper **III**. In this data-set, 40% of the stations had records spanning less than 15 years, and more than 30% of the data were missing in 18% of the hydrological years (Paper **III**).

Errors in aggregated data in the region might be large and vary in time and space. For example, data-collection procedures are not uniform over the region, so that each data set might display a different range of errors depending on the institutions involved. Also, each measurement station has different record lengths for different time periods. These errors are difficult to understand when all the data are combined.

Methods

Flood hazard assessment at basins with data limitations was studied at the local scale (Paper **I**, **II**) and at the regional scale (**III** and **IV**). Each paper focuses on different flood prediction aspects that can be useful for flood hazard assessment: Prediction of flood hydrograph (Paper **I** and **II**), water-level reproduction and flood hazard mapping (Paper **II**), flood-frequency analysis (paper **III**) and long-term flow series useful for flood-frequency analysis (Paper **IV**). Each papers deals with development of techniques and/or use of alternative data to cope with the scarcity and quality of data available in the region. The approaches used can be broadly classified as follows: Correction of errors from data input (Paper **I** and **II**), alternative modelling techniques (Paper **II** and **III**), and alternative data to locally observed hydrometric data (Papers **II**, **III** and **IV)**. Table 1 offers a scheme of the method, followed by a description of the details.

*Table 1 Development of techniques and alternative data in papers **I** to **IV**. Papers **III** and **IV** concern regional information*

Objective	Developed technique or used alternative data	**Paper I**	**Paper II**	**Paper III**	**Paper IV**
Develop techniques for flood prediction under conditions of data limitations	Rainfall multiplier	Correct spatial-average rainfall	Correct spatial-average rainfall		
	The MCT for unmeasured river cross-sections		Flood wave propagation		
	Combination of flow routing, ERRM, hydraulic model and uncertainty analysis		Reproduce an extreme flood		
	Combination of index-flood with GRADEX			Produce a FFC	
Explore the usefulness of unconventional sources of information for flood prediction	Long-term precipitation			Extend a FFC	
	Event precipitation		Drive an ERRM		
	Post-event measured hydrometric data		Drive and constrain an ERRM and a hydraulic model		
	Hydro-climate variability information				Constrain an RRM

Accounting for input-data errors

A method for accounting for the errors in rainfall input to ERRM was tested in Paper **I**, in a gauged catchment in China (Fig. 1). It was assumed that the behavioural parameter sets of a model calibrated against various flood events were a good representation of the system, and that a spatially and temporally averaged event-dependent rainfall multiplier could be identified from those sets. Thus, the search of the multiplier was computationally less demanding than allowing it to interact with all model parameters.

A range was chosen to sample the multiplier based on the statistics of the error obtained at all the available rain gauges in the catchment. The errors at each station were estimated by comparing the station's observed values with those estimated by spatially averaging the observed values at the remaining stations. Multipliers from the sampling range were then allowed to interact with all behavioural sets. The multiplier that best fit the observations for each behavioural parameter set according to the Nash-Sutcliffe model efficiency measure (NSE) was retained. Thus, a multiplier distribution per each event was obtained.

It was tested if the posterior multiplier distributions were event dependent, in which case the posterior distribution could provide information on the rainfall-event multiplicative error. Accounting for this rainfall error at calibration was expected to result in a more informative residual of the error between simulations and observation, useful for better assess of the parameter-sets likelihood. At prediction, information of the distribution of the multiplier could be obtained by the joint posterior multiplier distributions for all the calibrated events. The method was tested for 6 extreme flood events using the technique of leaving one event out at a time (the event to be estimated). Improvement by using or not using a multiplier at calibration and prediction was tested by using reliability- and precision-evaluation techniques (Laio and Tamea, 2007).

An account of a multiplier was also done in the case where rainfall data were used to drive an ERRM (Paper **II**) for an unmeasured flood event at three sub-catchments (Fig. 1). Thus, calibration of the ERRM against various events was not possible and the parameters were allowed to vary from a range. An explicit consideration of such a multiplier is expected to help to avoid other parameters from compensating for such errors (Beven and Binley, 2014) and to improve model results (Kuczera et al., 2006).

Model combination and alternative data for reproducing an extreme flood event

A combination of flow routing, an ERRM, a hydraulic model and an uncertainty analysis method was explored in Paper **II** in order to overcome the problem of a lack of event-measured hydrographs for the upstream boundary conditions of the Tegucigalpa city floodplain in Honduras (Fig. 1).

The hydrographs for the upstream boundary condition of a hydraulic model were obtained by combining TOPMODEL (Beven and Kirkby, 1979) and the Muskingum-Cunge-Todini flow routing, MCT (Todini, 2007). MCT was used to account for the sudden release of water from a dam. The MCT routing was adapted for cases where there was a lack of data for the river cross-sections by using the Tewolde and Smithers (2007) procedure. To account for the topographic relief in the area, the TOPMODEL was adapted for a slope-dependent varying hillslope velocity as in Grimaldi et al. (2010) (tested in Paper **I**). This way both MCT and TOPMODEL were combined to produce the hydrographs at three sub-catchments upstream from the floodplain.

Likely hydrographs were produced, using the GLUE method, to reflect the uncertainties in the model parameters and in the errors of the spatially-averaged input rainfall (which could be significant for some events [Paper **I**]). The hydrographs were therefore expected to be associated with large uncertainties, and those that were within the limits of acceptability (Liu et al., 2009) of the post-event measured data used for calibration, maximum peak discharge and time of the peak, were chosen as behavioural. Representative hydrographs from the behavioural sample were chosen using a clustering technique and were then used to interact with all model parameter sets of the hydraulic model. This way each interaction was evaluated regarding the limits of acceptability assigned to the maximum peak discharge, the times of the peak and high-water marks along the flood plain, all measured post-event. Thus, various parameter sets of the hydraulic model, each associated with a likelihood, were considered a good representation of the hydraulic system of the floodplain and were used to reproduce the extreme flood event.

Regionalisation for flood prediction

Model combination and alternative data for regional flood-frequency analysis

The usefulness of precipitation series to improve and extend the flood-frequency curve (FFC) produced at ungauged basins using regional information of flow series was tested by combining the index-flood (Dalrymple, 1960) and the GRADEX methods (Guillot and Duband, 1967; Paper **III**). The index-flood method is based on the assumption that the shape of the FFC is similar across catchments from a homogeneous region, where such a homogeneous region can be identified using geographical boundaries as in Paper **IV** or climate and catchment characteristics (Merz and Blöschl, 2005; Rosbjerg et al., 2013) as in Paper **III**. Thus, catchments in the region are expected to display a degree of similarity in the flood response. It was tested if the area, the annual average rainfall and the average slope of the catchments could help to further group the region into hydrologically more homogeneous sub-regions. Where homogeneity was assessed by similarity in the coefficient of variation of the annual maximum flood peaks series.

Estimated FFC using the index-flood regionalisation method are expected to be associated with large errors, particularly at the tail, when the length of the record of the stations in the region are not long enough to capture the flood variability (Guillot, 1993; Stedinger et al., 1992). On the other hand, the FFC at the tail is expected to reflect local characteristics of the storm frequency (Guillot, 1993). The shape of the storm frequency distribution might be catchment dependent as local variability of rainfall is expected particularly large in the region (Westerberg, 2011). Thus, it was tested whether the FFC estimated from the index-flood could be improved and extended using information about the local storm frequency. Improvements of the index-flood FFC are possible to obtain for catchments that follow the GRADEX assumptions: the frequency curve for a *d*-duration of storms and floods have an asymptotically exponential upper tail distribution with the same scale parameter (Guillot and Duband, 1967). For such catchments, the tail of the index-flood produced FFC can be corrected and extended by forcing it to follow the shape of the storm frequency distribution.

Regional hydro-climatic information as alternative data for model evaluation

It was tested if climate information on the Pacific side of Central America could help to constrain daily discharge series produced by an RRM (Paper **IV**). Based on hydro-climatic information, the following criteria were used to reject a model realisation:

a) Intra-annual constraint: discharge series that did not have a strong correlation with precipitation at the monthly scale.
b) Inter-annual constraint: discharge series which were uncorrelated with the Caribbean low-level-jet index (CLLJ) variation at the inter-annual scale.
c) Statistics of low-flow constraint: discharge series for which the value of the daily flow that is exceeded 99% of the time (low-flow) was

outside of the uncertainty limits of the value in the region obtained at Beck et al. (2015).

d) Long-term Budyko constraint: discharge series with a ratio between the long-term-estimated aridity index and the runoff ratio was outside the uncertainty limits assigned to the value obtained from 36 catchments in the region by Westerberg et al. (2014). The aridity index was estimated as the potential evapotranspiration divided by the precipitation, and the runoff ratio as the discharge divided by the precipitation, all long-term.

Results

Accounting for input-data errors

A spatially averaged event-dependent rainfall multiplier could account for errors due to spatially averaged rainfall (Paper **I**). The multiplier could be identified using the behavioural parameter sets, which had a negligible effect on its identified value. However, the value was mainly dependent on the rainfall-input error particular to each event, since the multipliers' posterior distribution came from different populations for most of the events (Fig. 2). It was found that the effect of this multiplier greatly improved hydrograph estimations at calibration when the identified multiplier was largely different from one (Fig. 3a). Accounting for those errors at prediction decreased the resolution but yielded an increase in the accuracy. However, when an event with a large error (odd event) was not included in the calibration, the identified distribution of multipliers, as expected, could not account for that error at prediction (Fig. 3c).

Paper **I** showed that the effect of rainfall-input error could be significant for some events. The multiplier obtained for an ungauged flood event in Paper **II** could also be identified, and the mean of the posterior distributions were different for different upstream sub-catchments.

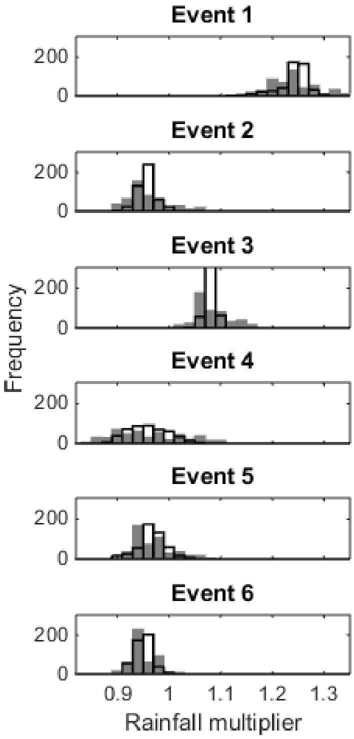

Figure 2. Frequency distribution of identified best multipliers for different events (top to bottom), with and without adjustment for the effect of parameter sets on the multipliers (black and grey outlined bars respectively).

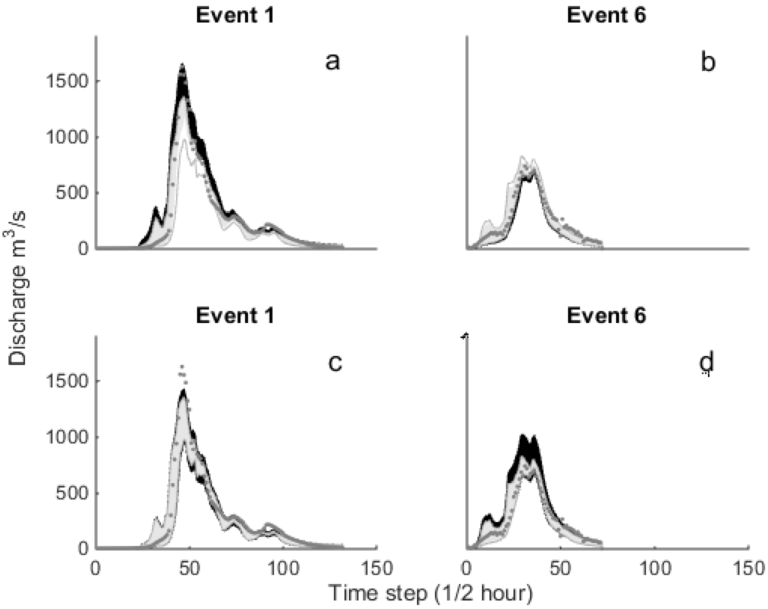

Figure 3. Predictive ranges of the 95% probability limits, using multipliers (black), and not using multipliers (grey) and observed flows (grey dots) for events 1 and 6 at calibration (a and b respectively) and the same events at validation (c and d respectively).

Model combination and alternative data for reproducing an extreme flood event

The estimation of the likelihood associated hydrographs that occurred during an extreme unmeasured event was made possible by the use of measured precipitation data and post-event hydrometric data (Paper **II**). A combination of a flow-routing model and an ERRM could overcome the difficulties of the lack of a measured hydrograph upstream of the floodplain. The use of the MCT flow routing for unmeasured cross-sections together with the TOPMODEL led to a group of behavioural hydrographs. Thus many possible hydrographs, behavioural ones, were obtained which could be reduced to a few representative samples using a clustering technique (Fig. 4). Combinations resulting from the interaction of those representative hydrographs with the uncertain hydraulic-model parameters led to the identification of the model behavioural parameter sets which were associated with a certain likelihood. These likelihood-associated parameter sets were used to obtain a likelihood estimation of the extreme flood event (Fig. 5).

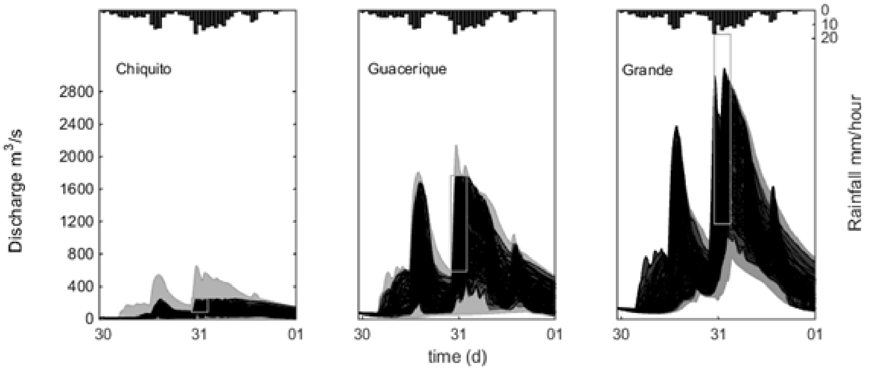

Figure 4. Precipitation (bars) and 100 class hydrographs chosen from the behavioural ones (black plots) for the sub-catchments of the Chiquito, Guacerique and Grande Rivers floodplain-upstream sub-catchments. Predictive range of the 100% probability limits for all hydrograph simulations (grey shaded area) and rectangles representing the fuzzy set to allow for uncertainty for peak discharge and time of the peak.

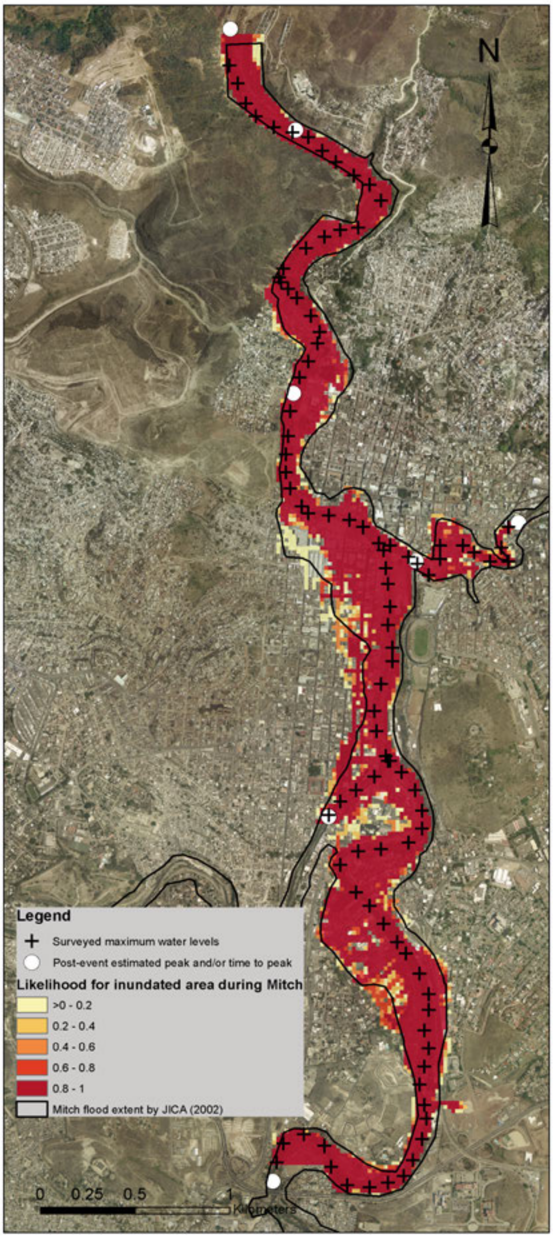

Figure 5. Likelihood of inundated area during the Mitch event on 30–31 October 1998, considering uncertainty in model parameters, model input and evaluation data to drive and constrain a combination of rainfall–runoff and hydraulic modelling tools. The deterministic flood extent was obtained by digitalisation of the flood extent in JICA (2002).

Regionalisation for flood prediction

Model combination and alternative data for regional flood-frequency analysis

The catchments in the region could be grouped into two sub-groups based on catchment annual average rainfall and area (paper **III**). This sub-grouping led to two marked flood-frequency behaviours in the region (Fig. 6) and thus to an increase in homogeneity.

The combination of the index-flood and the GRADEX methods made it possible to obtain improvements in the general estimation of the FFC at ungauged basins (Paper **III**).

Regional information was useful for flood-frequency analysis at the ungauged basin. The discharge record from neighbouring basins produced accurate predictions of the FFC at ungauged basins by using the index-flood approach. Predictions improved when sub-grouping the region (third column Fig. 7) instead of assuming that all catchments came from the same homogeneous region (fourth column Fig. 7).

Catchments for which base-time (i.e. the average duration of an event hydrograph) was much shorter than a day showed inconsistencies in the observed FFC, and they did no showed improvements from GRADEX methods. Most of the remaining catchments, a total of 36, benefited by complementing the index-flood method with the GRADEX method, which included some catchments that despite being associated with high outliers i.e. observations with lower recurrence than the length of the flow record, when these were excluded, also benefitted from the GRADEX method. This was not obvious in the estimated errors but was detected by visual inspection, one example is shown in Fig. 8. Sub-grouping of the region did not significantly decrease the errors when corrections by the GRADEX were applied.

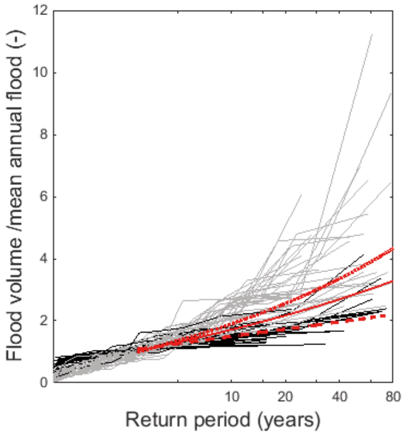

Figure 6. Growth curves for sub-region groups G1 and G2 (Grey and black solid lines respectively) found based on area and annual average rainfall catchment characteristics. Dotted, dashed and solid red lines show the regional growth curves for G1, G2 and all the catchments in the study area respectively.

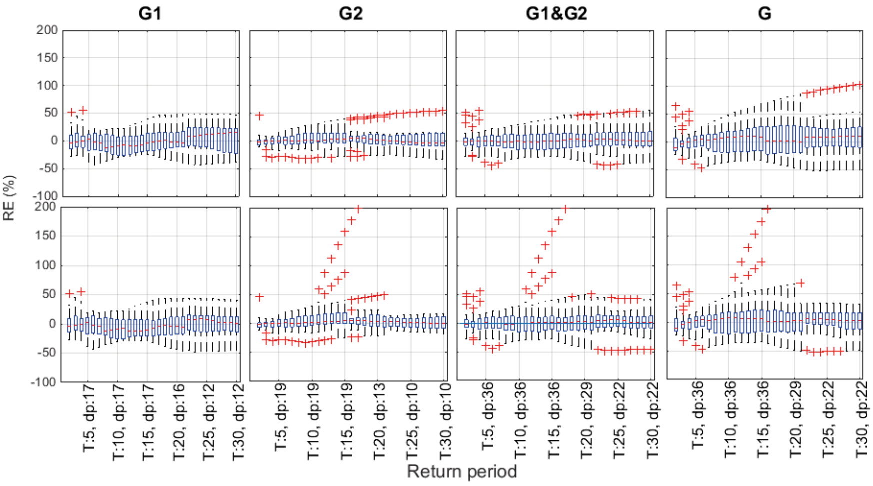

Figure 7. Boxplots of the relative error (RE) for prediction for different return periods (T), each one having different number of data points (dp) depending on the flow-record length. Plots were made using different groups of homogeneous regions (columns) using the index–flood only and a combination of the index–flood and the GRADEX (first and second rows respectively) methods. Estimations were made using the mean annual flood (MAF) as index-flood. Boxes correspond to the 20th, 50th and 80th quantiles, whiskers extend to 1.5 times the interquartile range and red crosses are outliers.

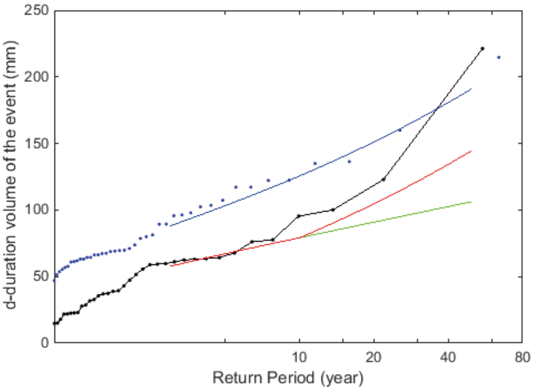

Figure 8. Observed d–duration flood–volume frequency curve (black) (FVFC), observed d–duration storm–volume frequency curve (blue dots) and fitted with generalised extreme value distribution (GEV) (continuous blue) predicted FVFC using index–flood (green) using the catchment mean annual flood as index and index–flood prediction improved by the GRADEX method (red).

Regional hydro-climatic information as alternative data to constrain a model

Paper **IV** showed that hydro-climatic information from catchments at the Pacific side of the Central American mountain ridge was useful to reject non-behavioural parameter sets from a hydrological model (Fig. 9). Information of long-term values of low-flow was more effective in constraining the simulations than those compared with climate variability. When only those constraints associated with climate variability were considered, the correlation of precipitation and discharge at the intra-annual scale did better.

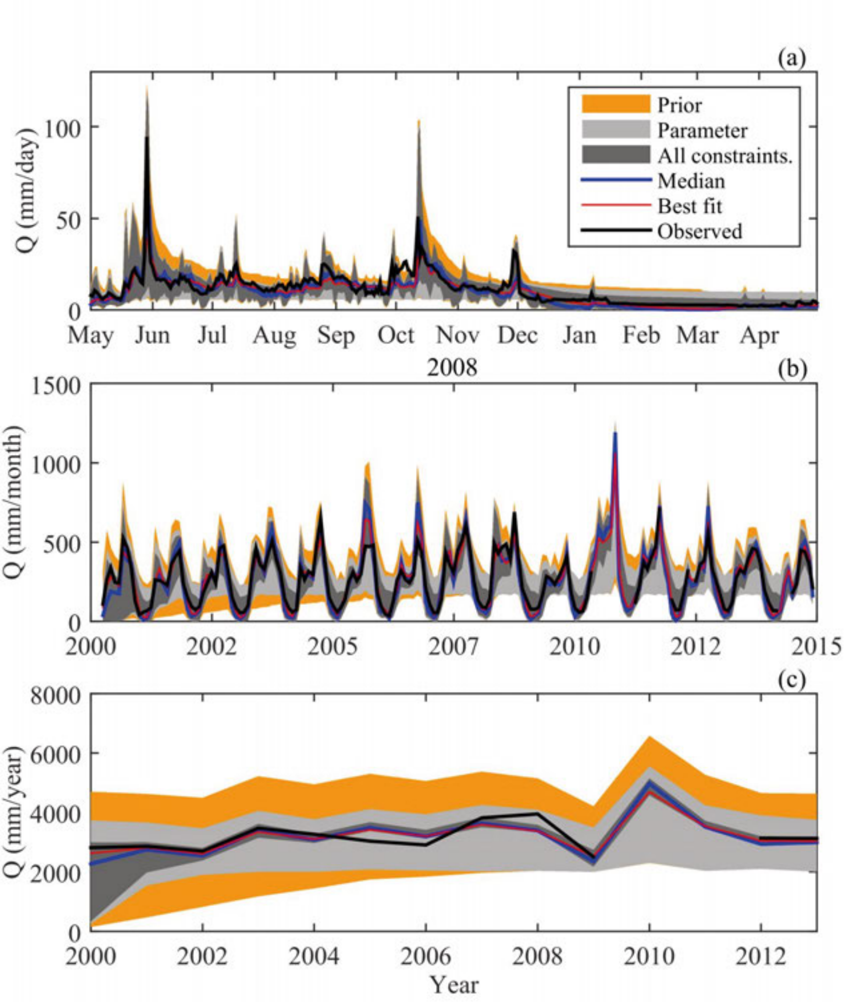

Figure 9. Predictive range of the 100% probability limit of the discharge for the prior, parameter-constrained and hydro-climatic constrained posterior distributions at daily, monthly and annual time scales (from top to bottom respectively).

Discussion

The purpose for this work was to develop new methodologies and to exploit alternative sources of data to support studies of flood hazard assessment in areas with data limitations.

Results from Paper **I** showed that a simple event-dependent rainfall multiplier could account for errors from spatially averaged rainfall from a sparse gauge network used as input to a hydrological model (Fig. 2). Accounting for these errors improved the calibrated and predicted flood hydrographs in terms of accuracy at the cost of a small reduction in precision in the latter (Fig. 3). Thus, consideration of errors in the spatial average rainfall, even through a simple multiplier, could prevent model parameters compensating for those errors (Beven and Binley, 2014), which in turn could improve model results (Kuczera et al., 2006; McMillan et al., 2011), enabling more representative error residuals useful for model improvements.

When a prior distribution of a rainfall multiplier was not available for prediction in an ungauged basin, expert knowledge of its range was used to explicitly account for such error (Paper **II**). The multiplier interacted with all other sources of uncertainty, however its posterior distribution was expected to be mainly associated with the rainfall-input error (Paper **I**). The mean of the posterior distribution of the rainfall multiplier for different sub-catchments suggested that the error of the spatially averaged rainfall varied in space for the same event.

Accounting for a rainfall error through a multiplier led to an accurate prediction in the peak magnitude, but did not account for the error in predicting the time of the peak flow. Errors in the time of the peak are expected to be decreased only by having a more representative measurement network (Younger et al., 2009). Thus, a denser and more efficiently distributed rain-gauge network or radar estimates should be prioritised in the areas at risk for flooding.

A flood-wave-propagation routing was explored by adapting the MCT when river topographic data were lacking (Paper **II**). The combination of such a routing with an ERRM might be useful for the propagation of rapidly varying flow conditions, such as release from a dam. The combination might also be an option to have a more localised model parameterisation at the main channel, from the MCT, while keeping a more compounded representation of the parameters, from the ERRM, in the upstream area. Still, the method proposed here should be tested with event-measured data.

A well-established rain-gauge network in combination with field campaigns for collection of topographic and hydrometric information after an event can be a viable alternative to reproduce an extreme flood event in a data-scarce area. Here, an unmeasured extreme flood event was reproduced using a suitable model combination together with rainfall and post-event-measured hydrometric data within an uncertainty-analysis framework. Although not explored here, high-resolution topographic data are important to drive the hydraulic model (Horritt and Bates, 2001). Such data can be obtained post-event from airborne laser scanning or photogrammetric surveys. Under unfavourable environmental and economic limitations other alternatives such as the Global Navigation Satellite System (GNSS) technique might be useful (Domeneghetti et al., 2015). The lack of observed hydrographs as input to the hydraulic model was overcome by the combination of MCT routing and an ERRM. The hydrographs could be constrained using uncertainty-associated post-event-measured data (Fig. 4). Thus, errors from input rainfall, model structures, model parameters and post-event topographic and hydrometric data were reflected in the behavioural parameter sets from the hydraulic model. These parameter sets were then used for the likelihood mapping of the extreme flood event (Fig. 5). The posterior parameters distribution obtained by calibrating the model(s) against several events to avoid model-parameter dependency on the event magnitude (Romanowicz and Beven, 2003) can also be used for prediction. Mismatch between observations and predictions after having considered the main sources of uncertainty might help to identify areas for improvement in the models or post-event-estimated data procedures.

Several assumptions were explicitly made to choose and quantify the different sources of uncertainty in order to estimate the behavioural parameter sets and from them the likelihood flood hazard map. The modeller usually makes these assumptions. If stakeholders were involved this could improve the way they make decisions, since they would benefit from a better understanding of the uncertainties (Beven et al., 2015).

The index-flood regionalisation method performed well at predicting the FFC at ungauged basins in the region. Performance was largely improved by grouping the region into two homogeneous sub-regions based on annual average rainfall and area catchment characteristics. The lack of sufficient stations with a long and high-quality observation record limits the number of sub-groups that could be made and the use of formal statistical test for homogeneity (Meigh et al., 1997; Paper **III**). The index-flood method was limited by the record length of the stations, which prevent a trustworthy use of the FFC for large return periods.

Through the combination of the index-flood and the GRADEX methods it was possible to improve and therefore extend FFC estimated only from the index-flood. The improvement was not successful, however, for catchments with a base-time much shorter than one day. This might be due to data commensurability errors that are expected to be larger for small and short-response catchments in this study (Westerberg et al., 2014 and Paper **III**). In addition, the temporal resolution of the data was lower than the response time for those catchments which prevented identification of isolated flood events (Paper **III**). Nearly all the catchments for which the index-flood method could be assessed benefited from being complemented with the GRADEX method (Fig. 7). Thus, the FFC might be extended for some of the catchments in the region with only short discharge record by using local information of storm frequency. When no local flow record is available, regional information of flow record can be used, through the index-flood method, in combination with the GRADEX method (Paper **III**).

The GRADEX assumptions are expected to be better fulfilled by small catchments because they have a higher likelihood of a peak flow resulting from the rainfall contribution from the whole upstream area (Gupta, 2004; Smith et al., 2015). Therefore for those catchments a better linear relationship between flood and storm, assumption from the GRADEX, are more likely. Thus, the applicability of the methodology for those catchments remains to be tested using local rainfall data with a higher spatiotemporal resolution than the gridded precipitation used here. For cases where GRADEX applies, the usefulness of the method could be further explored by using projections of precipitation obtained from climate change scenarios (e.g. Tripathi et al., 2006). There are two advantage of using projection of precipitation, through the GRADEX, instead of discharge for FFA that considers climate change scenarios, one is that the GRADEX method relies only on the frequency of the precipitation and not in the magnitude. Secondly, projection of precipitation are more accurate than estimation of the discharge based on those projections, as the latter one involves more modelling processes and therefore more sources of uncertainties (Buytaert et al., 2010).

Simulations from a hydrological model were largely constrained by using hydro-climatic information in the region (Fig. 9) (Paper **IV**). The constraints were set to take advantage of the similarities in the values of Budyko-relation and low-flow in the region. Similarities in the correlation between precipitation and discharge at the intra-annual scale and correlation between the Caribbean low-level-jet index (CLLJ) and discharge at the inter-annual scale in the region were also useful to constrain the models. The general discharge characteristics tended to follow those of the precipitation at the intra-annual (Paper **IV**) and inter-annual (Waylen and Laporte, 1999; Paper **IV**) temporal scales in the region. Catchments in the region are therefore responsive to precipitation, as expected from the mountainous terrain characteristics in the area. Since the hydrological behaviour responded to the climate variability, climate features in the region (e.g. Amador et al., 2006; Maldonado, 2016) could further be exploited by linking them to similarities in hydrological response across catchment scales (Blöschl et al., 2013; Sivapalan, 2003; Wagener and Montanari, 2011). The similarity in hydrological response in the region (Westerberg et al., 2014; Paper **III** and Paper **IV**) needs to be further exploited through regional studies. The development of regional studies in the area can be fostered by the availability of regional, global and satellite data sets of different catchment descriptor.

Alternative data were shown here to offer a great value in addition to or in place of locally observed hydrometric data to drive, constrain and improve the result of modelling tools for flood prediction. The data explored here came from discharge series in the region, as well as post-event hydrometric measurements, climate-variability information and local long-term and event-based precipitation data.

Practical applications of the results

Throughout this thesis a series of steps were taken that can be used to support flood-risk-management systems, through the mapping of the likelihood of flood hazard, in a basin with data limitations.

Flood-frequency analysis (FFA) can be carried out in ungauged basins by using regional flow information and local precipitation data (Paper **III**), and by reproducing discharge series using precipitation as input to an RRM, which can be constrained using regional hydro-climatic information (Paper **IV**). An ERRM calibrated with post-event-estimated data (Paper **II**) can be used to convert flood-peak magnitude (from FFC) to a hydrograph by assuming a pattern of a high-intensity-rainfall event. If flood magnitude from a FFC is unavailable, a storm associated with a probability of occurrence, obtained from a rainfall series, can be used as input to an ERRM in order to obtain the probability-associated flood hydrograph, where the ERRM could be set to account for errors in rainfall input from a sparse gauge network (Paper **I**). Such hydrographs can be used as input to a hydraulic model, also calibrated with post-event data (Paper **II**) in order to obtain the spatially distributed likelihood of a flood hazard. The likelihood levels will depend on the uncertainty assigned to the data and model parameters, which ideally should be jointly decided by the modeller and the stakeholders.

The propagation of various sources of uncertainties, especially from data (Papers **I**, **II** and **IV**), leads to larger predictive ranges than in cases where local observations of the predicted variable are available (Hrachowitz et al., 2013; Sivapalan et al., 2003). Uncertainties are also particularly significant during high- and low-flow conditions (Clarke, 1999; Westerberg, 2011). It is therefore recommended that such a process of calibration for flood prediction purposes is done within a Bayesian framework of updating the model parameters when more observations, including post-event-measured ones, become available.

Conclusions

This thesis has explored methods as well as use of unconventional sources of information to support flood hazard studies in conditions of scarcity and lack of high-quality data. A methodology to account for the multiplicative error in spatially averaged rainfall was developed to improve estimation of the hydrographs from rainfall-runoff models. A suitable combination of models, post-event hydrometric data, measured precipitation and uncertainty analysis were useful for calibrating a hydraulic model and thereby reproducing the likelihood-associated flood hazard map for an unmeasured extreme event. Long-term precipitation data were useful for improving and extending a flood-frequency curve obtained from a regionalisation method for ungauged basins. Long-term precipitation data were also important for reproducing discharge series where the lack of observations for calibration were handled with hydro-climatic information from the region.

Some of the methods used here were dependent on and limited by the spatio-temporal resolution of the precipitation data. A better spatiotemporal characterisation of these data will greatly benefit flood hazard assessments in the region. Investments in collection of such data should be prioritised, especially since such data can compensate for the lack of discharge records, which are difficult or impossible to obtain during extreme events.

Hydro-climatic information was valuable for prediction in ungauged basins in the region. Similarities in the hydrological dynamics of catchments and its link with climate variability need to be further explored in Central America. Availability of regional or global data of catchment descriptors will be beneficial for development of regional studies.

Post-event hydrometric data is an alternative to reproduce an extreme flood event, a fair spatial cover of these data and the measurement of various events, can be useful to calibrate hydraulic models useful for flood hazard assessment and forecasting.

Hydrometric data are important for flood hazard assessment, and their measurements should be enhanced in low-income countries. The development of techniques and use of alternative data were explored here to assist when such data are scarce or of bad quality. The methods used here considered the uncertainties inherent in the modelling process, which are especially important under data-limited conditions. The predictive uncertainties are expected to be reduced when new data, even unconventional ones, become available for incorporation in the analyses.

Results from flood hazard assessment in the form of likelihoods that reflects the uncertainties in the modelling processes, as presented here, are meant to be integrated in flood-risk-management systems and to be use by Stakeholders. These should be prepared to make decisions under these unavoidable uncertainties. The results produced here can be used to make decisions which will hopefully contribute in reducing the loss of life and economic value caused by flooding in low-income nations.

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Sammanfattning på svenska (summary in Swedish)

Extremt höga vattenflöden ställer till stora problem i hela världen. De skadar infrastruktur och egendom och orsakar död. Framför allt kan låg- och medelinkomstländer vara väldigt sårbara för extrema flöden p.g.a. deras ekonomiska, sociala, politiska och kulturella sårbarheter. Konsekvenserna kan dessutom förvärras genom den pågående klimatförändringen. I dessa länder saknas dessutom ofta data som behövs för att kunna bedöma översvämningsrisker, eller så finns bara data av dålig kvalitet.

Denna avhandling föreslår nya metoder som använder okonventionella informationskällor vid bedömning av översvämningsrisker i områden där traditionella hydrologiska data saknas eller har otillräcklig kvalitet. Arbetet fokuserar på Mellanamerika och består av fyra delstudier, två i lokal och två i regional skala.

En metod utvecklades för att ta hänsyn till fel i rumslig medelnederbörd beräknad från ett glest nät av nederbördsmätare. En multiplikator för medelvärdesbildad nederbörd, i tid och rum, för enskilda högflödestillfällen bestämdes under antagande av att det gick att identifiera parametervärdesuppsättningar som resulterade i modellkörningar med god representation av avrinningsområdets hydrologiska egenskaper under högflödesepisoder. Identifieringen av parametervärdesuppsättningarna skedde inom ramen för osäkerhetsanalysen GLUE (Generalised Likelihood Uncertainty Estimation). Användning av multiplikatorn ledde till förbättringar i de kalibrerade flödestopparna genom bättre felresidualer som kan komma till nytta i form av modellförbättringar. Genom att använda multiplikatorfördelningar, identifierade från tidigare högflödestillfällen i avrinningsområdet, kunde också prognoser förbättras.

En andra metod använde sig av möjligheten att reproducera ett extremt högflöde inom ramen för en osäkerhetsanalys med hjälp av en kombination av modeller, nederbördsdata och hydrometriska data som uppmätts i efterhand. Denna kombination gjorde det möjligt att identifiera parametervärdesuppsättningar med hophörande sannolikheter ur vilka det gick att erhålla en sannolikhetsbaserad översvämningskarta för det höga flödet. I ett följande skede skulle parametervärdesuppsättningar som kalibreras vid flera högflödessituationer kunna användas för prognoser inom ett Bayesianskt ramverk.

En tredje och fjärde studie i regional skala utforskade värdet av likheter mellan avrinningsområden och hur det hydrologiska gensvaret i områdena beror av klimatet.

Kurvan för kumulativa högflödesfrekvenser (flood frequency curve, FFC) kunde skattas med hjälp av information om nederbördsfrekvens, från lokala tidsserier, och regional information om korta tidsserier av vattenföring från 36 avrinningsområden som antogs sakna vattenföringsdata. Detta möjliggjordes genom att två etablerade metoder för analys av högflödesfrekvenser användes, indexflödesmetoden och GRADEX-metoden. Felen i skattningarna varierade inom ett rimligt intervall vilket gör den kombinerade metoden användbar där det saknas lokala data för en säkrare analys. Det gick inte att utvärdera kombinationsmetoden för små avrinningsområden med kort svarstid p.g.a. otillräcklig tidsupplösning och bristande jämförbarhet med data, som är större för små avrinningsområden Det gick inte att utvärdera kombinationsmetoden för små avrinningsområden med kort svarstid p.g.a. otillräcklig tidsupplösning och bristande jämförbarhet med data. Detta är ett problem som är större för små avrinningsområden.

I den andra regionala studien visade sig hydroklimatisk information av värde för att avgränsa godtagbara prognoser för daglig vattenföring från en hydrologisk modell. Detta gjordes genom att jämföra simuleringar som korrekt återgav givna hydrologiska karaktäristika och värden i regionen, t.ex. korrelationen mellan nederbörd och avrinning på en inomårsskala, korrelationen mellan CLLJ-indexet (Caribbean low-level jet) och avrinning på mellanårsskala samt långtidsvärden på sambandet mellan lågflöden och Budykokurvan.

Tidigare beskrivna metoder, använda tillsammans med okonventionell information inom ramen för en osäkerhetsanalys, visade sig vara användbara för att bedöma översvämningsrisker i avrinningsområden med databegränsningar. Bland utforskade data fanns: mätningar i efterhand av ett extremt högflöde, hydroklimatisk regional information och lokala nederbördsmätningar.

Mätningar i efterhand av hydrometriska data var ett alternativ till traditionella hydrologiska data för att kunna reproducera ett extremt högflöde. En strategiskt planerat rumslig efterhandsmätning av sådana data och mätningar vid olika högflödesepisoder kan användas för att kalibrera en hydraulisk modell som blir användbar för prognoser och bedömning av översvämningsrisker.

Några av metoderna som använts i denna avhandling var beroende och begränsade av upplösningen i tid och rum hos nederbördsdata. En bättre karaktärisering av dessa data skulle därför vara till mycket stor hjälp vid bedömning av översvämningsrisker. Investeringar i sådan datainsamling bör ges hög prioritet, i synnerhet eftersom sådana data kan kompensera för brister i data på vattenföring som är svår att registrera eller behäftad med stora fel vid extrema högflödestillfällen.

Regional hydroklimatisk information visade sig värdefull för prognoser i avrinningsområden utan vattenföringsdata. Likheter i avrinningsområdens hydrologiska dynamik och deras länk till klimatets variation skulle behöva studeras ytterligare i regionen. Utvecklingen av regionala studier i området kan gynnas av tillgången till regionala, globala och satellitdata av olika egenskaper hos avrinningsområdena.

Hydrometriska data är betydelsefulla, ja rent av avgörande, för bedömning av översvämningsrisker. Insamling av sådana data skulle behöva förbättras i många låg- och medelinkomstländer. Denna avhandling har fokuserat på utvecklingen av metoder och användning av alternativa data när tillgången på traditionella hydrometriska data är begränsad eller data är av dålig kvalitet. Metoderna som används här tar hänsyn till den inneboende osäkerheten i modelleringsprocessen som är speciellt viktig under databegränsade förhållanden. Prognososäkerheten förväntas minska när nya data, även okonventionella sådana, kan användas i analysen.

Resultat presenteras här i form av sannolikheter som återspeglar modelleringsprocessens osäkerheter vid bedömning av översvämningsrisker. Dessa osäkerheter är avsedda att integreras i de riskhanteringssystem som används av berörda myndigheter och organisationer. Intressenter i riskhanteringssystemet måste ta beslut givet dessa oundvikliga osäkerheter. Resultaten här är tänkta att kunna användas av intressenterna för att ta informerade beslut. Därigenom kan förhoppningsvis arbetet bidra till att begränsa förluster i människoliv och ekonomiska förluster som orsakas av extrema högflöden och översvämningar såväl i låg- och medelinkomstländer som höginkomstländer.

Resumen en español (summary in Spanish)

Inundaciones traen como consecuencia el daño de infraestructura, propiedad y pérdida de vidas a nivel mundial. El daño por las inundaciones es más severo en países de bajos ingresos debido a la vulnerabilidad económica, social, política y cultural a los que están expuestos. Las consecuencias por inundaciones podrían empeorar en dichos países debido al cambio climático y los datos hidro-climatológicos que se necesitan para realizar estudios de manejo de riesgo por inundación son escasos o no tienen la calidad suficiente para dichos propósitos.

Esta tesis propone nuevos métodos para explotar fuentes no convencionales de información para la evaluación de riesgo por inundaciones en áreas con limitaciones en la cantidad o calidad de los datos. El presente trabajo está enfocado en la región centro americana y está compuesto de cuatro estudios, dos de ellos fueron desarrollados a la escala local y dos a la escala regional.

Un método fue desarrollado para considerar el error asociado a la precipitación promedio sobre cuencas en modelos lluvia-escorrentía cuando se usa una red de estaciones de lluvia dispersa. El error se asumió como un factor multiplicador del histograma del evento, el cual se pudo identificar para todos los eventos durante la calibración asumiendo que varios parámetros del modelo (antes calibrados) son una buena representación del sistema hidrológico de la cuenca. Los parámetros del modelo y el factor multiplicador fueron identificados usando el sistema de análisis de incertidumbre GLUE. El factor multiplicador ayudó a mejorar los hidrogramas estimados durante calibración obteniendo así una mejor representación del residuo de los errores lo cual beneficia iniciativas para la mejora de los modelos hidrológicos. Los hidrogramas para la predicción también fueron mejorados a cambio de una pequeña reducción en precisión de la incertidumbre.

Mediante un segundo método fue posible reproducir un evento extremo de inundación el cual no contaba con medidas hidrométricas. Dicha reproducción fue posible mediante el uso de una combinación de modelos hidrológicos e hidráulicos, datos recopilados después del evento, datos de precipitación registrados durante el evento y utilizando un método de análisis de incertidumbre. Esto permitió obtener combinaciones de parámetros asociados a una probabilidad que sirvieron para producir el mapa de riesgo de inundaciones del evento extreme.

El tercer y cuarto estudio fueron hechos a la escala regional para explorar el valor de las similitudes entre las cuencas en la región y el efecto que el clima tiene en la respuesta hidrológica de las cuencas. Se estimaron curvas de frecuencia de inundaciones para 36 cuencas, asumidas no aforadas, usando registros de caudal de corta duración disponibles en la región e información local sobre la frecuencia de las tormentas. Esto fue posible mediante el uso de dos métodos ya establecidos en literatura, el método de índice de inundación y el método de GRADEX. El error en las estimaciones varió dentro de un rango razonable que puede ser útil para predecir en cuencas no aforadas. Esta metodología no pudo ser evaluada para cuencas pequeñas con un tiempo de respuesta corto debido a la resolución temporal y el error de conmensurabilidad de los datos, el cual es significativo para dichas cuencas.

En el cuarto estudio, se encontró que la información hidro-climatológica tiene un gran valor para reducir el rango de incertidumbre de las simulaciones de caudal diaria de un modelo hidrológico. Esto fue hecho comparando que las simulaciones del modelo estén en conformidad con ciertos valores y características hidrológicas en la región (p. ej. correlación entre precipitación y descarga a la escala intra-anual, correlación entre la corriente en chorro de bajo nivel del Caribe (CLLJ) y descarga a la escala inter-anual, y el valor de la relación Budyko y de los caudales bajos para la serie de tiempo).

Los métodos anteriormente descritos usados en combinación con datos no convencionales dentro de un método de análisis de incertidumbre han demostrado ser útiles para la evaluación de riesgo por inundaciones en cuencas con limitaciones en los datos. Los datos en esta tesis incluyen: datos hidrométricos recopilados o estimados después de un evento extremo de inundaciones, datos hidro-climatológicos de la región y datos locales de precipitación.

Datos hidrométricos recopilados o estimados pasado el evento de inundación fue una alternativa para reproducir un evento extremo de inundaciones, y una cobertura espacial estratégicamente planificada de estos datos después de varios eventos puede ser útil para la calibración de modelos hidráulicos para la evaluación de riesgo por inundación.

Varios de los métodos usados en esta tesis dependieron y fueron restringidos por la resolución espacio-temporal de los datos de precipitación. Una mejor caracterización de dichos datos beneficiara grandemente estudios dirigidos para la evaluación de riesgo por inundaciones. Inversión en la recolección de datos de precipitación debe ser priorizado ya que dichos información puede compensar la falta de aforos de caudal, los cuales son difíciles de obtener o están asociados con grandes incertidumbres para eventos extremos.

Datos hidro-climatológicos de la región fueron de gran valor para predicción en cuencas no aforadas, dichos datos se usaron como calibración, en vez de datos observados, para restringir los resultados de un modelo hidrológico. Similitudes entre la dinámica hidrológica de las cuencas y el vínculo de estos con la variabilidad del clima necesitan ser investigados más en la región. El desarrollo de estudios regionales en el área se beneficiaría de la disponibilidad de datos regionales, globales y satelitales sobre información descriptiva de las cuencas.

Datos hidrométricos son importantes para la evaluación de riesgo por inundaciones y la recolección de dichos datos debe ser fortalecido en países en desarrollo. El desarrollo de técnicas y el uso de datos alternativos fueron explorados para asistir cuando dichos datos son escasos o de mala calidad. Los métodos aplicados en esta tesis han considerado las incertidumbres propias en los procesos de modelaje hidrológico, las cuales son particularmente grandes en situaciones de datos limitados. La incertidumbre para predicciones se espera pueda reducirse cuando más datos convencionales y no convencionales se vuelven disponibles para incorporarlos en los análisis.

Los resultados de la evaluación del riesgo por inundación presentados en términos de probabilidad, como se hizo en esta tesis, reflejan las incertidumbres en los procesos y están diseñados para ser integrados dentro de un sistema de manejo del riesgo por inundaciones. Se requiere que las partes interesadas estén preparados para la toma de decisiones bajo fuentes de incertidumbre que son inevitables. Los resultados producidos aquí se pueden usar para tomar decisiones, y se espera que el presente trabajo pueda ser usado para tomar decisiones que contribuyan a la reducción de vidas y pérdidas económicas causadas por las inundaciones en los países de bajos ingresos.

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