UPPSALA UNIVERSITET

Digital Comprehensive Summaries of Uppsala Dissertations from the Faculty of Science and Technology 1753

Flood Prediction in data-scarce basins

Maximising the value of limited hydro-meteorological data

JOSÉ EDUARDO REYNOLDS PUGA

ACTA UNIVERSITATIS UPSALIENSIS UPPSALA 2019

ISSN 1651-6214
ISBN 978-91-513-0527-1
urn:nbn:se:uu:diva-368532

Dissertation presented at Uppsala University to be publicly examined in Axel Hambergsalen, Villavägen 16, Uppsala, Friday, 8 February 2019 at 10:00 for the degree of Doctor of Philosophy. The examination will be conducted in English. Faculty examiner: Professor Vazken Andréassian (Université Pierre et Marie Curie, Paris).

Abstract

Reynolds Puga, J. E. 2019. Flood Prediction in data-scarce basins. *Maximising the value of limited hydro-meteorological data*. *Digital Comprehensive Summaries of Uppsala Dissertations from the Faculty of Science and Technology* 1753. 70 pp. Uppsala: Acta Universitatis Upsaliensis. ISBN 978-91-513-0527-1.

Floods pose a threat to society that can cause large socio-economic damages and loss of life in many parts of the world. Flood-forecasting models are required to provide simulations at temporal resolutions higher than a day in basins with concentration times smaller than 24 h. However, data at such resolutions are commonly limited or not available, especially in developing or low-income countries. This thesis covers issues related to the scarcity and lack of high temporal-resolution hydro-meteorological data and explores methods where the value of existing data is maximised to improve flood prediction.

By varying the starting time of daily records (the day definition), it was shown that this definition had large implications on model calibration and runoff simulation and therefore, should be considered in regionalisation and flood-forecasting applications. A method was developed to treat empirically model-parameter dependencies on the temporal resolution of data. Model parameters seemed to become independent of the temporal resolution of data when the modelling time-step was sufficiently small. Thus, if sub-daily forcing data can be secured, flood forecasting in basins with sub-daily concentration times may be possible using model-parameter values calibrated from time series of daily data. A new calibration method using only a few event hydrographs could improve flood prediction compared to a scenario with no discharge data. Two event hydrographs may be sufficient for calibration, but accuracy and reduction in uncertainty may improve if data on more events can be acquired. Using flood events above a threshold with a high frequency of occurrence for calibration may be as useful for flood prediction as using only extreme events with a low frequency of occurrence. The accuracy of the rainfall forecasts strongly influenced the predictive performance of a flood model calibrated with limited discharge data. Between volume and duration errors of the rainfall forecast, the former had the larger impact on model performance.

The methods previously described proved to be useful for predicting floods and are expected to support flood-risk assessment and decision making during the occurrence of floods in data-scarce regions. Further studies using more models and basins are required to test the generality of these results.

Keywords: Floods, data scarcity, value of information, rainfall-runoff modelling, regionalisation, rainfall-forecasts, event-based calibration, climatological day, discharge day, temporal resolution, modelling time-step.

José Eduardo Reynolds Puga, Department of Earth Sciences, LUVAL, Villav. 16, Uppsala University, SE-75236 Uppsala, Sweden.

ISSN 1651-6214
ISBN 978-91-513-0527-1
urn:nbn:se:uu:diva-368532 (http://urn.kb.se/resolve?urn=urn:nbn:se:uu:diva-368532)

Akademisk avhandling som för avläggande av teknologie doktorsexamen i hydrologi vid Uppsala universitet kommer att offentligen försvaras i Hambergsalen, Villavägen 16, Uppsala, fredagen 8 februari 2018, klockan 10:00. Fakultetsopponent: Professor Vazken Andréassian (Université Pierre et Marie Curie, Paris). Disputationen sker på engelska.

Referat

Reynolds Puga, J. E. 2019. Högflödesprognoser i avrinningsområden med bristfällig information. Maximering av värdet av begränsade hydrometeorologiska data. *Digital Comprehensive Summaries of Uppsala Dissertations from the Faculty of Science and Technology* 1753. 70 pp. Uppsala: Acta Universitatis Upsaliensis. ISBN 978-91-513-0527-1.

Översvämningar är ett samhällshot och ibland en naturkatastrof med förluster av människoliv och omfattande materiella skador på många ställen i världen. Översvämningsprognoser kräver modellsimuleringar av höga flöden med högre tidsupplösning än dygn i avrinningsområden där svarstiden understiger 24 h. Data med sådan tidsupplösning är ofta begränsade eller obefintliga, i synnerhet i låginkomstländer. Denna avhandling behandlar problem relaterade till brist eller avsaknad av hydrometeorologiska data med hög tidsupplösning och undersöker metoder för att maximera värdet av befintliga data för översvämningsprognoser.

Genom att variera starttiden på dygnsdata (dygnsdefinitionen), visades att definitionen hade stor inverkan på modellkalibrering och avrinningssimulering, och därigenom påverkade regionaliserings- och översvämningsberäkningar. En metod utvecklades för att empiriskt hantera modellparametrars beroende av indatas tidsupplösning. Modellparametrarna verkade vara oberoende av indatas tidsupplösning när modellens beräkningstidssteg var tillräckligt litet. Så om drivdata med inomdygnsupplösning kan säkerställas, är det möjligt att förutsäga översvämningar i områden med små svarstider på grundval av modellparametrar som kalibrerats mot tidsserier av dygnsdata. En ny kalibreringsmetod baserad på endast ett fåtal stora flödestoppar kunde förbättra översvämningsprognoser jämfört med en situation där flödesdata helt saknades. Två flödestoppar kan räcka för kalibrering men noggrannheten förbättras och osäkerheten minskar om fler toppar finns tillgängliga. Användning av flödestoppar över ett tröskelvärde som ofta överskrids kan vara lika användbart för kalibrering som användning av extrema, sällan förekommande högflöden. Precisionen av nederbördsprognoserna påverkade starkt den prediktiva förmågan hos en modell för höga flöden kalibrerad med en begränsad mängd vattenföringsdata. I jämförelse mellan felen i volym och varaktighet på regnprognosen, så hade den förra större inverkan på modellens resultat.

De beskrivna metoderna var användbara för högflödesprognoser och kan förväntas understödja bedömningen av översvämningsrisker och hanteringen av översvämningar i områden med begränsade data. Allmängiltigheten av resultaten behöver prövas med andra modeller och för andra avrinningsområden.

Nyckelord: databrist, flödestoppsbaserad kalibrering, högflöde, informationsvärde, klimatologiskt dygn, nederbörds-avrinningsmodell, modelltidssteg, regionalisering, regnprognos, tidsupplösning, vattenföringsdygn, översvämning.

José Eduardo Reynolds Puga, Institutionen för geovetenskaper, LUVAL, Villavägen 16, Uppsala universitet, 752 36 Uppsala.

ISSN 1651-6214
ISBN 978-91-513-0527-1.
urn:nbn:se:uu:diva-368532 (http://urn.kb.se/resolve?urn=urn:nbn:se:uu:diva-368532)

Defensa presentada en la Universidad de Uppsala para ser evaluada públicamente en el salón Axel Hambergsalen, en el Departamento de Ciencias de la Tierra, Villavägen 16, Uppsala, el viernes 8 de febrero de 2019 a las 10:00 a. m. para el grado académico de Doctor en Filosofía. Oponente académico: Profesor Vazken Andréassian (Université Pierre et Marie Curie, Paris).

Resumen

Reynolds Puga, J. E. 2019. Pronósticos de inundaciones en cuencas hidrográficas con escasez de datos. Maximizando el valor de datos hidro-meteorológicos limitados. *Digital Comprehensive Summaries of Uppsala Dissertations from the Faculty of Science and Technology* 1753. 70 pp. Uppsala: Acta Universitatis Upsaliensis. ISBN 978-91-513-0527-1.

Las inundaciones son una amenaza para la sociedad que pueden causar grandes daños socio-económicos y pérdida de vidas humanas en muchos lugares del mundo. En cuencas con tiempo de concentración inferior a 24 h se necesitan modelos que pronostiquen inundaciones con una resolución temporal superior al día. Datos hidro-meteorológicos a esas resoluciones suelen no estar disponibles o no existen, especialmente en países en desarrollo. Esta tesis cubre temas relacionados con la escasez de datos de alta resolución temporal y explora distintos métodos en los que el valor de los datos existentes se maximiza para mejorar la predicción de inundaciones.

Al variar la hora de inicio del día en las observaciones se demostró que la definición del día tuvo un gran impacto en la calibración del modelo y en las simulaciones de caudal, lo cual puede tener un efecto en la regionalización de parámetros hidrológicos. Se desarrolló un método para gestionar empíricamente la dependencia de los parámetros con respecto a la resolución temporal de los datos. Los valores de los parámetros se volvieron independientes de la resolución temporal de los datos cuando el intervalo de tiempo del modelo fue configurado en pasos suficientemente pequeños. Como resultado, si se pudiesen obtener datos de entrada en resoluciones temporales sub-diarias, sería posible hacer pronósticos de inundación en cuencas con tiempo de concentración menor a un día utilizando parámetros calibrados con series de tiempo de datos diarios. Se desarrolló un método de calibración basado en unos cuantos hidrogramas de crecidas para hacer pronósticos de inundaciones más robustos en comparación con el escenario de no tener ninguna observación. Dos hidrogramas de crecidas mostraron ser suficientes para calibrar el modelo, pero las predicciones podrían ser más precisas y con menos incertidumbre si se pudiese disponer de datos de un mayor número de eventos. El uso de crecidas por encima de un umbral con una alta probabilidad de ocurrencia resultó ser igual de útil para la calibración del modelo que el uso de eventos más extremos, que ocurren con menor frecuencia. La precisión de los pronósticos de lluvia impactó altamente el rendimiento de un modelo de inundación previamente calibrado contra un número limitado de crecidas. Entre los errores de volumen y duración en los pronósticos de lluvia, el primero tuvo el mayor impacto en los resultados del modelo.

Los métodos descritos en esta tesis demostraron ser útiles para predecir inundaciones y se espera que contribuyan a una mejor evaluación del riesgo de inundaciones en regiones con escasez de datos. Se requieren estudios adicionales que utilicen más modelos y cuencas para probar la generalidad de estos resultados.

Palabras claves: inundaciones, falta de datos, valor de información, modelos lluvia escorrentía, regionalización, pronósticos de lluvia, definición del día, resolución temporal, paso de tiempo.

José Eduardo Reynolds Puga, Universidad de Uppsala, Departamento de Ciencias de la Tierra, Villavägen 16, SE-75236 Uppsala, Suecia.

ISSN 1651-6214

ISBN 978-91-513-0527-1.

urn:nbn:se:uu:diva-368532 (http://urn.kb.se/resolve?urn=urn:nbn:se:uu:diva-368532)

A mi familia.

List of Papers

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

I **Reynolds, J. E.**, Halldin, S., Seibert, J. & Xu, C. Y. (2018). Definitions of climatological and discharge days: do they matter in hydrological modelling? *Hydrological Sciences Journal*, 63:5, 836-844, DOI: 10.1080/02626667.2018.1451646

II **Reynolds, J. E.**, Halldin, S., Xu, C. Y., Seibert, J., & Kauffeldt, A. (2017). Sub-daily runoff predictions using parameters calibrated on the basis of data with a daily temporal resolution. *Journal of Hydrology*, 550, 399–411, DOI: 10.1016/j.jhydrol.2017.05.012

III **Reynolds**, **J. E.,** Halldin, S., Seibert, J., Xu, C. Y. & Grabs, T. (2018). Robustness of Flood-Model Calibration using Single and Multiple Events. In review. *Hydrological Sciences Journal*

IV **Reynolds**, **J. E.,** Halldin, S., Seibert, J., Xu, C. Y. & Grabs, T. (2018). Flood prediction using uncertain rainfall forecasts and parameters calibrated on limited discharge data. *Manuscript*.

Reprints were made with permission from the respective publishers.

In **Paper I**, I contributed to the formulation of the research questions and design of the experiments. I performed the analysis and wrote the manuscript with contributions from all co-authors. In **Paper II**, I contributed to the design of the research experiment with support from all co-authors. I performed the analysis and prepared the manuscript with contributions from all co-authors. In **Papers III** and **IV**, I contributed defining the research questions, defining the experiment, performing the analysis, and was the main responsible for writing the manuscripts.

Contents

Abbreviations

A_k	Transformation constant
CEH	Centre for Ecology & Hydrology database
ECMWF	European Centre for Medium-Range Weather Forecasts
ENSO	El Niño-Southern Oscillation cycle
EPS	Ensemble prediction system
$F_1(\Theta)$	Mean volume error of the events
$F_2(\Theta)$	Mean RMSE of the events
$F_3(\Theta)$	Mean peak flow error of the events
$F(\Theta)$	Aggregate measure of $F_1(\Theta)$, $F_2(\Theta)$ and $F_3(\Theta)$
FRMS	Flood risk management systems
GA	Genetic algorithm
GLUE	Generalised likelihood uncertainty estimation
HBV	Hydrologiska Byråns Vattenbalansavdelning model
ITZC	Intertropical Convergence Zone
LST	Local standard time
MC	Monte Carlo
MORECS	Meteorological Office Rainfall and Evaporation Calculation System
NERC	Natural Environment Research Council
M_p	Number of events in calibration or evaluation
NWP	Numerical weather-prediction
P_E	Relative peak-flood error
R_{eff}	Nash-Sutcliffe efficiency
RMSE	Root-mean-square error
T_E	Relative time-to-peak error
UNESCO	United Nations Educational, Scientific and Cultural Organization
USGS	United States Geological Survey
UTC	Coordinated Universal Time
V_E	Relative volume error
WMO	World Meteorological Organization

Introduction

"What is not started will never get finished"
–Johann Wolfgang von Goethe

Floods can cause detrimental consequences on society, economy and environment in many parts of the world. On average, about 21 million people worldwide are affected by river floods each year (Luo *et al.*, 2015). The effects of floods are notably severe in developing or low-income countries because of their vulnerability to the occurrence of these phenomena.

Central America is one of the regions in the world most exposed and vulnerable to climatological risks (Dilley *et al*., 2005; Mucke *et al*., 2017; UNESCO, 2012). Floods caused by the occurrence of extreme rainfall are the natural disasters that most often occur and that have affected more the Central American region (Marengo *et al.*, 2014, UNESCO, 2012). The occurrence of large-scale events in Central America usually causes large amounts of economic and human life losses (e.g., when Hurricane Mitch hit the region back in 1998, close to 11,000 people died because of flooding, about 2.7 million lost their homes and flood damages were estimated to be over 6 billion USD) (Lott *et al.*, 1999). Moreover, the region is impacted every year by small–medium scale flood events, that together cause more damage than large-scale events (UNESCO, 2012).

During the last 60 years, climate trends in Central America have not shown a significant increase in total amount of rainfall, but the number of events with high rainfall intensities have increased (Marengo *et al.*, 2014). This has resulted in the occurrence of more floods and an increase of flood economic losses, and this trend is expected to continue (WMO, 2011). Although the latter has raised awareness on society to be better prepared for the occurrence of these phenomena, socio-economic development (i.e., population growth, urbanisation, expansion on floodplain areas), limited quantity and quality of observational hydro-meteorological data (Reynolds, 2012; Westerberg *et al*., 2010), economic constraints, or passive participation of local authorities in flood-forecasting systems have left the region lacking of resilience, anticipation and adaptive capacities to cope with these extreme events and therefore, making the region more vulnerable to the phenomena (Marengo *et al.*, 2014, UNESCO, 2012).

Lack of hydro-meteorological data for model calibration has always been an issue for predicting floods in ungauged basins. In Central America, as in many other regions, where floods occur frequently and basins are small–medium sized (~100–1000 km^2) with concentration times smaller than 24 h, there is a demand for flood-forecast models at sub-daily temporal resolutions. Any application of those models relies on the availability of long-time series of sub-daily observational data, which are commonly rare. Modelling with data at the temporal resolution needed is not always an option, which leaves hydrologists with no other option than to make use of the best data available, if any, to improve the understanding and representation of hydrological processes of such complex hydrological systems. In addition, the lack of quality of the data available in Central America has been one of the main reasons for the limited number of studies or publications made in the region, which has made it more complicated for researchers or practitioners to come up with conclusive statements that could help in good planning (Fuentes-Andino, 2017, Marengo *et al.*, 2014, Quesada-Montano, 2017, Reynolds, 2012).

Reliable and accurate prediction of floods in data-scarce basins using hydrological models is a challenging task. Commonly, their parameters cannot be directly estimated from measurements or basin characteristics and, thus, some calibration is needed to reduce errors in predictions. Data needs in hydrological models are scale dependent (e.g., the higher the temporal and spatial resolutions of the predictions needed, the higher are the data requirements) (McGlynn *et al.*, 2013). As technology, modelling has grown and large data sets over large spatial scales have become available for hydrological applications (e.g., remote sensing), whereas the number of conventional stations has declined in recent years (Stokstad, 1999). This happened even though the value of hydrological data, in terms of benefits, is considered higher than the cost of collecting them (Cordery & Cloke, 1992). If limited observational data are or become available in data-scarce basins, then exploring methods to assess how valuable such data could be for meaningful predictions of floods becomes relevant. Ultimately, the available data and developed methods should allow effective responses based on reliable flood-risk predictions.

Another problem that arises when predicting floods in fast-response basins is that peak discharges tend to occur as a result of a localised rainfall event and times to peak may be too short for raising adequate warnings based on real-time rainfall observations (Ferraris *et al.*, 2002). In these conditions, the only option is to raise warnings of potential flooding based on rainfall forecasts.

Although new technologies and methods have emerged for improving the accuracy of rainfall forecasts, rainfall forecasts are still the main source of uncertainty in flood forecasting, which limits the usability of hydrological models in real-time applications (Kobold, 2007). Given the current-state-of-art on the accuracy of rainfall forecasts, only flood warnings are feasible and further studies in such area are needed to improve their prediction skills.

This thesis covers issues related to the scarcity and lack of high temporal-resolution hydro-meteorological data and explores methods where the value of existing data is maximised to improve flood prediction. The present study is mainly focused in the Central American region and includes four studies, which were carried out at the local scale.

Aim of this thesis

The overall goal of this thesis was to enhance water resources and flood management in data-scarce basins with sub-daily responses by maximising the value of limited hydro-meteorological data.

In more details, the aims of the thesis were divided into two main parts:

a. Improving the understanding of the effects of data-related uncertainties on hydrological models (**Papers I, II** and **IV**).
b. Developing methods to improve the robustness of runoff- and flood-model calibration using limited hydro-meteorological data (**Papers II**, **III** and **IV**).

Background

Flood concepts

Floods are defined as a rising of a body of water that covers an area of land that is normally dry. In general, there are three major flood types: river flooding, coastal flooding and urban flooding (Maskey, 2004). This thesis is limited to river flooding, which is characterised by rapid or slow rises of water above their bank levels and subsequently inundating the land around it.

The time it takes for floods to build up varies from site to site. In relation to the latter, floods in snow-free basins can be classified as flash floods, short-rainfall floods and long-rainfall floods (Maskey, 2004; Sikorska *et al.*, 2015). Flash floods are common in mountainous areas during the rainy season and are characterised by a rapid and massive increase of water volume, often combined with debris flow. They are often caused by rains of short durations (less than half a day) and with intensities that exceed the infiltration capacity of soils. Flash floods occur quickly and build up within a few hours after the occurrence of rainfall, leaving communities with little time to respond and imposing a major challenge to hydrologists to alert for the occurrence of these events (Maskey, 2004, WMO, 2011). Short-rainfall floods are caused by rains with high intensities that last a maximum of one day. Long-rainfall floods are characterised by slow water level rise and by gradual inundation of floodplain. The latter type is generally caused by continuous (lasting several days) and low intensity rainfall events that eventually fill soil-storage capacity (Sikorska *et al.*, 2015).

Flood risk planning and management

Floodplain areas of many rivers worldwide have been considerably modified because of many global issues (e.g., population and economic growth, degradation of ecosystem services). Usual impacts of urban developments include the reduction of the response time of basins and the increase of water volume and peak runoff (Rosbjerg *et al.*, 2013). This together with climate variability and climate change have increased flood risks. The World Meteorological Organization (WMO) defines risk as the probability of detrimental consequences to human lives, environment, loss of life, property and resources caused by interactions between natural or human hazards and vulnerable conditions (WMO, 2011). The characterisation of flood risks deals with many sources of uncertainty, of which socio-economic issues are expected to be the largest one in the future (WMO, 2011).

Adequate warnings allow people to protect themselves and their property from the harmful effects of floods. Flood risk management systems (FRMS) emerged as a response to the increase of floods and to satisfy community-safety and property-protection expectations (WMO, 2011). These systems are based on the execution of systematic actions in a cycle of preparedness, response, recovery and mitigation (WMO, 2011). Flood risk identification, risk analysis, risk assessment and risk reduction through appropriate policies and practices are developed within flood risk management systems as a combined effort between decision makers and experts (Schanze *et al.*, 2006).

The implementation of any flood risk plan requires knowledge of water levels or flood peaks. Two types of flood predictions are required. One is the prediction of floods in terms of magnitude and timing at a particular location, together with its inundation extent during its occurrence (i.e., flood water level). This type of prediction is often required in short-term flood preparedness systems to raise timely flood warnings. The second one is the prediction of a high water level or peak discharge likely to occur in the future (i.e., improving knowledge of the frequency of occurrence of floods of different magnitudes) (Beven, 2001, Rosbjerg *et al.*, 2013).

In the design and planning processes of flood risk management plans, decisions are made on a level of uncertainty and some risk of failure is accepted (i.e., balance between cost and losses because of budget limitations) (WMO, 2011). Additionally, flood protection measures are typically designed to deal with certain flooding limits. However, the capacity of these protections may be exceeded for the most extreme events (Beven, 2001). Since these measures cannot protect society completely from flooding, flood forecasting becomes an essential part of flood management (WMO, 2011). The role of flood forecasting is different for each case, and it would be expected that the temporal and spatial resolutions of meteorological and hydrological forecasts fit the conditions of the place of interest.

Modelling techniques for flood prediction

One issue that arises in predicting floods is when the natural time delay in a basin is not sufficiently long to assure enough lead time for responses to be put in place (Beven, 2009, WMO, 2011). Sufficient lead time is location specific, varies from minutes to hours or days and depends on the basin's size, river length, river-bed slope and location within a region or country (Romanowicz *et al.*, 2006; WMO, 2011). The magnitude of flood peaks is relative to the interplay between rainfall durations and the mean response time of the basin (Rosbjerg *et al.*, 2013). The largest floods are often triggered by storms with durations equal or longer than the basin's response time. Usually, small basins have short concentration times, whereas large basins have long concentration times. Because of the latter, flood forecasting modelling in small basins is primarily made using rainfall-runoff models, together with radar rainfall, telemetering rainfall data or rainfall forecasts, whereas in large basins, this usually involves rainfall-runoff and hydraulic models. This thesis is limited to flood predictions using rainfall-runoff models in small basins with sub-daily responses.

Three types of models are usually referred in the literature regarding their mathematical representation of hydrological processes: physical, empirical and conceptual models (Xu, 2002). Physically-based models represent hydrological processes more realistically based on laws of continuity, energy and momentum. Empirical models have little physical significance and are generally developed using input and output data taken simultaneously. Conceptual models are based on physical laws but in a highly simplified way (Xu, 2002). Spatial variability of the parameters depends on how the model is spatially setup: lumped, semi-distributed or distributed.

The choice of the model structure depends on many factors: modelling purpose (e.g., requirements of stakeholders), the degree of model complexity in relation to the data available, resource constraints and modeller's experience (Parajka *et al.*, 2013, WMO, 2011). Complex models, such as those physically-based and distributed, usually require large amounts of hydro-meteorological data, which are commonly not available in data-scarce conditions. Furthermore, the use of only runoff data for calibration of distributed models could be highly misleading for identifying model parameters (Blöschl *et al.*, 2008). In principle, parameters in physically-based models should be measurable. However, this may not be possible because of heterogeneity of the basin characteristics and processes complexity. Complex models usually have a large number of parameters to calibrate which could lead to calibration problems (e.g., overparameterisation, long simulation periods, especially at short temporal resolutions) (Beven, 2001). On the other hand, simple models (e.g., lumped and conceptual) often require little input data, have a considerably lower number of parameters, lower computational demands and have shown to provide as good modelling results for predicting discharge as more complex models (Beven, 2001; Bormann *et al.*, 2009; Franchini & Pacciani, 1991). Additionally, it is very unlikely that better results will be obtained using distributed instead of lumped models if the available data to represent the natural spatial variability of the basins are limited.

Physically-based distributed models are usually used in research to gain a better understanding of hydrologic phenomena, whereas conceptual-lumped models are more widely used for practical applications, water-resources planning and management. A typical conceptual hydrological model used to predict discharge in a lumped or semi-distributed way is the HBV model (Bergström, 1976; Lindström *et al*., 1997), which has been applied successfully in many basins with different climatological conditions (Häggström *et al*., 1990; Seibert, 1999; **Papers I–IV**). One model, the HBV-light version with its standard model structure set up in a spatially lumped way, was used in all the papers included in this thesis (model available at http://www.geo.uzh.ch/en/units/h2k/Services/HBV-Model.html).

Rainfall-runoff modelling has to deal with many sources of uncertainty related to the data, model and parameters. Therefore, it is advised that rainfall-runoff predictions should be presented within an uncertainty estimation framework given all these sources of errors (Beven & Binley, 1992). This was the case in **Papers II, III** and **IV**.

Flood modelling using rainfall-runoff models can be made event- or continuous-based. Event-based models simulate individual flood events in response to storms over basins. On the other hand, continuous-based models simulate flood response and moisture content continuously in time, taking into account all the precipitation that falls over the basins and the movement of water through them until it reaches their outlet (WMO, 2011).

Predicting floods in data-scarce basins

The main issue for predicting flood hydrograph in data-scarce basins is the lack of observational discharge data for the selection and calibration of an adequate model for prediction. After a suitable model has been chosen, model parameters need to be estimated. In conceptual models as the one used herein, parameters cannot be estimated a priori from measurements (from field experiments or remote sensing) because these are rather more empirical than physical representations (Parajka *et al.*, 2013).

If basins are ungauged, one approach to overcome this limitation is parameter regionalisation through statistical or process-based methods (e.g., transferring the calibrated parameters from gauged to ungauged basins) (Blöschl *et al.*, 2013). If some observational data are available, these are often at a daily resolution. Two approaches have been proposed to bridge the gap between the daily temporal resolution of the data and the timescale at which fast-flow processes occur. One approach is to use daily-calibrated parameters to simulate runoff at sub-daily resolutions. This approach is applicable when a time series of sub-daily input data is or can be made available to force the model (**Paper II**). However, if basin responses occur at timescales finer than daily, it is worth noting that the starting time of the day of the data could affect model calibration (**Paper I**) and result in inaccuracies of daily parameters (Littlewood & Croke, 2008) and poor model performance (Bastola & Murphy, 2013). The second approach consists of scaling model parameters when transferring them across temporal resolutions (Bastola & Murphy, 2013; Ficchì *et al*., 2016; Finnerty *et al*., 1997; Nalbantis, 1995; Ostrowski *et al*., 2010; Wang *et al*., 2009).

If time and resources were available, it could be argued that the best approach would be to perform field measurements, preferably including time periods representative of the processes occurring in the basins to be modelled (Seibert & Beven, 2009; Tada & Beven, 2012, **Papers III** and **IV**). In such data-limited conditions, it becomes relevant on estimating how valuable a small amount of data could be (**Papers III and IV**) and how sensitive flood predictions are to errors in rainfall forecasts (**Paper IV**).

Research gaps and opportunities

Predicting floods in data-scarce basins is limited by the availability of good and sufficiently long time series of sub-daily rainfall and discharge observations for model calibration. However, this limitation also gives opportunities for improving knowledge and flood-management practices. For instance, if the solution is to transfer parameters across temporal resolutions without scaling, for example from daily to hourly, one question that arises before going through this procedure is whether the starting time of the day – referred here as the definition of the day – of the daily records affects parameter estimates and runoff prediction. Although the effects on rainfall-runoff models caused by several uncertainties related to hydro-meteorological data have been widely investigated (Andréassian *et al*., 2001; Gan *et al*., 1997; Jie *et al*., 2018; Xu *et al*., 2013), those caused from the definition of the day have received little interest (Jian *et al*., 2017; Vincent *et al*., 2009; Westerberg *et al*., 2014). The answer to this question could have consequences for regionalisation and flood forecasting. This was investigated in one study (**Paper I**) where model performances obtained using different definitions of the climatological and discharge days were compared.

Equally important, flood managers may wonder whether the transferability of parameters across temporal resolutions result in a significant decrease in model performance. Parameters calibrated at different temporal resolutions have been shown to vary considerably, to be dependent on the temporal resolution of data (Bastola & Murphy, 2013; Kavetski *et al*., 2011; Littlewood, 2007; Littlewood & Croke, 2008; Ostrowski *et al*., 2010) and to be influenced by the rainfall intensity-duration relationship (Wang *et al.*, 2009). Causes of these dependencies have been attributed to the loss of information of the physical processes as the data are averaged over coarser temporal resolutions (Littlewood & Croke, 2008, 2013, Ostrowski *et al.*, 2010). A study on the impact of temporal resolution of data on parameter inference by Kavetski *et al*. (2011) shows that false strong parameter temporal-resolution trends emerge when unreliable modelling time-stepping schemes or numerical methods are implemented to solve model equations. They argue that using robust numerical methods and heteroscedastic residual-error models stabilises and reduces the strength of model-parameter dependencies on the temporal resolution of data. A study in line with the latter authors (**Paper II**), tested the hypothesis that temporal-resolution dependencies of the parameters of a bucket-type hydrological model may be neglected when a common numerical resolution or modelling time-step is implemented.

Lack of resources for the establishment and maintenance of permanent discharge stations has been one of the reasons for the interest of researchers and practitioners on knowing how valuable small amounts of data might be for model calibration. Several studies on parameter and performance variability caused by the length or quantity of the calibration data have reported good modelling predictions (Anctil *et al*., 2004; Brath *et al*., 2004; McIntyre & Wheater, 2004; Melsen & Teuling, 2014; Seibert & Beven, 2009; Sorooshian *et al*., 1983; Tada & Beven, 2012; Yapo *et al*., 1996). Results of these studies diverge from site to site and are difficult to generalise as a unique solution for data-scarce conditions. This topic was further investigated in two studies (**Papers III and IV**).

In the first (**Paper III**), it was hypothesised that adequate model calibration in a data-scarce environment is possible when hydrographs of only a few events are available, and assessed the value of such events in terms of quantity and information content. The second study (**Paper IV**) also deals with flood-model calibration based on limited discharge data, as in the former, and tested the hypothesis whether event hydrographs above a threshold with a high frequency of occurrence can be useful in calibration to provide reliable flood predictions. Furthermore, this study assessed the importance of rainfall-forecast errors for meaningful predictions of floods in such data-limited conditions. The motivation of the latter study was to contribute in knowledge on how errors in the rainfall forecasts affect flood predictions.

Overall, all studies included in this thesis are interesting from a research and practical perspective, and contribute to the ultimate goal of enhancing water-resources and flood management in basins with sub-daily responses and data-limited conditions.

Study area

Two basins were selected to carry out the investigations included in this thesis, one in Panama and one in the United Kingdom. The selection of these basins was based on their characteristics and their data availability for each study. In this regard, the tropical Boqueron River basin (Fig. 1), located in Panama (Central America), was selected because it had data at a high temporal resolution adequate for performing the analysis in all the papers included in this thesis (**Papers I–IV**) and because it represents a typical basin in Central America that frequently suffers the effects of floods. Similarly, the headwater region of the temperate Wye River basin (Fig. 2), located in mid-Wales, was selected because it has been the subject of many water-resources studies and because it also had data at a high temporal resolution adequate to explore on the transferability of model parameters across temporal resolutions (**Paper II**). Both basins have similar features (e.g., sub-daily lag-times, drainage areas under 100 km^2) and different seasonalities.

Boqueron River basin

The climate of Central America is highly variable in time and space. Rainfall in the region depends on: (1) the annual movement of the inter-tropical convergence zone; (2) the presence of northeast trade winds; (3) the mountainous terrain (Georgakakos *et al.*, 1999); and (4) the ENSO phenomenon (Ropelewski & Halpert, 1987). Rainfall is generally convective and orographic, and occurs mostly in the form of heavy downpours resulting from thunderstorms. Most of the rain falls between May and December, whereas the other months are relatively dry. The tropical Boqueron River basin was the study area in **Papers I–IV**. Forests predominantly covered the 91 km^2 basin, and its elevation ranges from 100 to 980 m a.s.l. (USGS, 2016). The basin has 1−3 h lag times (i.e., time difference between the peak precipitation and the peak discharge). The 1997–2011 mean annual rainfall in the basin is 3,800 mm y^{-1} and runoff 2,728 mm y^{-1}.

Areal precipitation was estimated by Thiessen polygons from four stations of hourly rainfall data, available within and close to the basin for 1997−2011. Rainfall forecasts were needed in **Paper IV** but these were not available for the basin. Instead, several rainfall-forecast scenarios were generated based on real-time observations but with volume and duration errors added.

The stage at the Peluca station was recorded continuously in a nonstationary river-cross section using a float inside a stilling well and stored every 15 minutes. Stage-discharge ratings at this station were made at least once a month and rating-curve updates were made in case of change. Hourly maximum-annual discharge for 27 years (1985–2011) and 15 years of continuous discharge data (1997–2011) were available. Daily pan evaporation data for the period 1985−2010 from the Tocumen station, located 36 km southeast of the basin, were used to estimate long-term daily mean values of potential evaporation. The hydro-meteorological data of this basin were quality-controlled in **Paper II**.

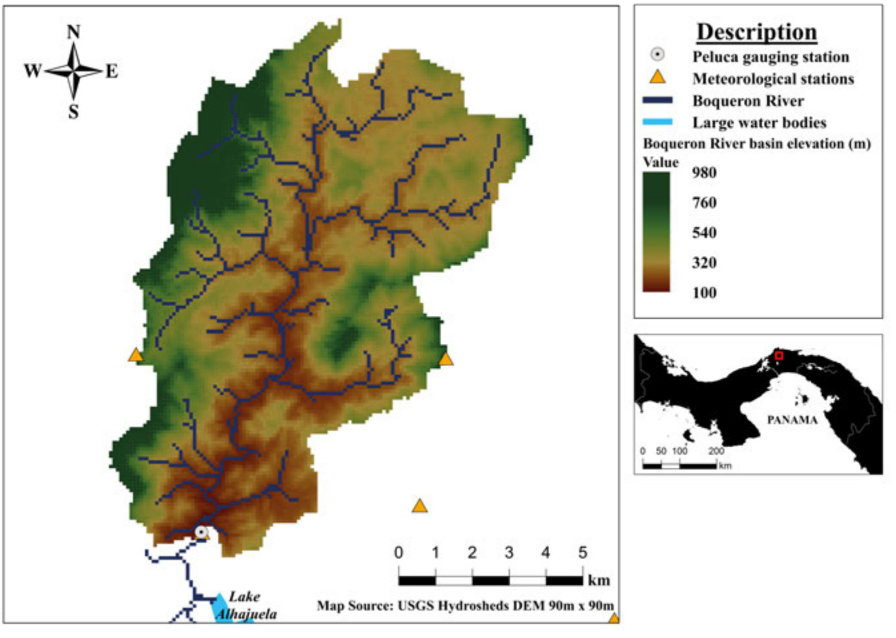

Figure 1. Location of Boqueron River basin in Panama. This basin was the study area in **Papers I–IV**.

Wye River basin

The headwater region of the temperate Wye River basin at Cefn Brwyn was the second basin used in **Paper II**. The 10.6 km^2 basin is one of the Plynlimon research basins operated by the Center for Ecology and Hydrology (United Kingdom), and is predominantly covered by open moorland for grazing sheep. It is a flashy basin with 1−3 h lag times. Its elevation ranges from 341 to 735 m a.s.l. (CEH, 2016) and it is characterised by rolling hills. Most of the rainfall falls in the autumn and early winter months (October−January), while the late spring and early summer months are considerably drier. The mean annual rainfall is 2,490 mm y^{-1} and runoff 2,170 mm y^{-1} (NERC, 2003).

Precipitation was measured by two hourly meteorological stations, stage was gauged at a 3-bay Crump profile weir and calculated discharge was stored every 15 min. The rainfall-runoff data of the Wye River basin at Cefn Brwyn were made available online at http://tdwg.catchment.org/datasets.html. The data were at the 1-h temporal resolution, covered a 2-year period (1 Jan 1987–1 Jan 1989) and were not quality-controlled for their use because they were considered to have a high quality. Long-term monthly MORECS potential evaporation estimates for South Britain for the period 1961−1990, available from Kay & Davies (2008), were used as a reference for the basin but corrected for differences in altitude based on a methodology by Finch & Hall (2001).

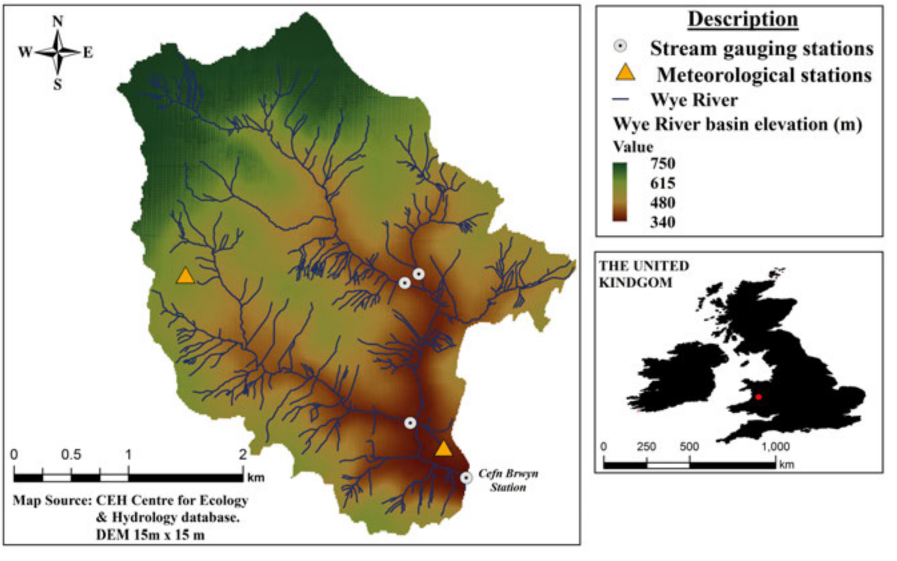

Figure 2. Location of the Wye River basin in Wales. This basin was one of the study areas in **Paper II**.

Methods

"Research is what I'm doing
when I don't know what I'm doing!"
–Wernher von Braun

Modelling implications of day definition

The aim of **Paper I** was to assess how different definitions of the climatological and discharge days affected a rainfall-runoff model. This was done in four steps. First, 1-h rainfall and runoff data were aggregated to 12 different sets of daily values (i.e., different 24-h intervals). A first daily time series resulted from aggregating the 1-h data for the time interval 00−00, a second for the 02−02 interval, and consecutively every two hours until 22−22. Second, each of the 12 daily rainfall time series was disaggregated uniformly into 1-h time series to drive the model and generate 1-h runoff. Third, 1-h runoff simulations were aggregated to daily steps based on the 24-h interval for each of the 12 daily runoff time series. This resulted in 144 model set-ups (i.e., 12 daily rainfall time series, one for each climatological-day definition, for each of the 12 daily runoff time series). Fourth, an optimisation procedure based on a genetic algorithm (GA) was applied to each model set-up and their model performance was compared.

The differential equations in the HBV-light version are solved numerically using the explicit Euler and operator-splitting schemes (adding or subtracting fluxes in a distinct order). These simple methods can be numerically unstable and can return unreliable numerical solutions when used with a daily modelling time step. However, these schemes are expected to return numerical solutions approximate to the true or exact solution when the modelling time-step is sufficiently small. To avoid numerical artefacts, daily runoff was simulated with a 1-h modelling time step, for practical purposes, regardless of the daily input data.

Transferability of model parameters across temporal resolutions

The motivation of **Paper II** was to explore the possibilities of simulating sub-daily runoff where data at these resolutions are not available for calibration. Here, it was hypothesised that model-parameter dependencies caused by the temporal resolution of the data and by numerical issues might be neglected when a common numerical resolution or modelling time-step is implemented.

After the hourly precipitation and runoff datasets of the two basins chosen for this study were aggregated to 3-, 6-, 12- and 24-hourly time series, the existence of model-parameter dependencies on the temporal resolution of data was studied in two steps. First, by comparing the distribution of parameter values calibrated from Monte Carlo (MC) simulations of 1-, 3-, 6-, 12- and 24-hourly runoff using the explicit Euler method while simulating in modelling time-steps of 1 h. Second, a cross-temporal-resolution comparison of model performance was made, where calibrated parameter sets were used to simulate runoff at the other four temporal resolutions for which they were not calibrated. Similarly as in **Paper I**, runoff was simulated with a 1-h modelling time step, regardless of the temporal resolution of the input data, to avoid numerical artefacts.

Flood-model calibration based on limited discharge data

For the scenario of no discharge data available for calibration, knowing how valuable a small amount of data might be for such a purpose is critical knowledge. Two studies were carried out to address the latter question, which could help to improve the robustness in flood-model calibration (**Papers III** and **IV**).

In one study (**Paper III**), the model was calibrated on the basis of single and multiple events and then tested in validation to assess their ability to predict floods. In this study, it was hypothesised that adequate model calibration in a data-scarce environment is possible when hydrographs of only a few events are available. More specifically, this study aimed to answer how many high-flow events are needed in calibration to achieve an adequate flood prediction. Furthermore, the information content of individual extreme events was compared to determine how informative they were in calibration.

A subsequent study (**Paper IV**), focussed on the question of whether hydrographs above a threshold with a high frequency of occurrence can be useful in flood-model calibration and forecasting. Here, rainfall inputs in forecasting were assumed to have a quality as good as that of real-time observations. In addition, the effects of rainfall-forecast errors on a flood model calibrated on limited discharge data were assessed.

Two thresholds values were used to select the events for calibration: (1) the median annual flood, which is an extreme value with a low frequency of occurrence (489 $m^3 s^{-1}$ or 19. 4 mm h^{-1}, return period of 2.33 years) (**Papers III and IV**) and (2) a more relaxed threshold (125 $m^3 s^{-1}$ or 5 mm h^{-1}, return period of 1.01 years), which has a higher frequency of occurrence than the former. The first threshold is at the 50th percentile of the maximum-annual discharge data set, whereas the second is at the 1st percentile of the same data set and it is about four times smaller than the former. Ten events were found above the first extreme threshold, whereas 107 were found above the threshold with a higher frequency of occurrence.

Prediction performance in calibration was assessed for the different scenarios of data availability based on a joint objective function, $F(\Theta)$, which comprised three goodness-of-fit measures: (1) mean volume error of the events, $F_1(\Theta)$, (2) mean root mean square error (RMSE) of the events, $F_2(\Theta)$, and (3) mean peak flow error of the events, $F_3(\Theta)$. $F_1(\Theta)$ relates to relative volume error (V_E), $F_2(\Theta)$ to Nash-Sutcliffe efficiency (R_{eff}), and $F_3(\Theta)$ to relative peak-flow error (P_E).

Calibration based on single and multiple events

In **Paper III**, it was assumed that the number of event hydrographs available for calibration (M_p) varied from one to five. The model was calibrated for all possible event combinations for a given value of M_p. Calibrated parameters were subsequently used in validation to simulate floods and their predictive ability was assessed. Each event combination had its own number of behavioural parameter sets that resulted in specific model performances in validation. The median of those performances, referred here as median model performance, was computed for each event combination. Finally, median model performances achieved in validation were compared for different values of M_p. Here, median value of accuracy for every value of M_p is referred as the median of the median model performance values.

To assess the value of individual extreme events in terms of their information content, **Paper III** compared median model performances in validation based on the types of events used in calibration for each value of M_p. First, the ten calibration events were classified into three types based on their characteristics. Then, all possible event combinations for a given M_p were classified into three larger groups according to its event-type combination (Fig. 3).

Using a fixed number of multiple events in calibration, **Paper IV** explored if hydrographs above a threshold with a high frequency of occurrence can be useful in flood-model calibration and forecasting. Two sets of event combinations were generated based on events above thresholds with a high and a low frequency of occurrence. The HBV model was calibrated for both sets of event combinations and their flood predictive ability was tested in forecasting using a rainfall forecast with a quality as good as that of real-time field measurements. Median model performances in the validation of the two sets of event combinations were compared.

Median model performances in the validation period for **Papers III** and **IV** were compared to an upper and lower benchmark to show the value of the calibration data in comparison to when no data were available (Seibert *et al.*, 2018). The upper benchmark represented the best model performance that could be achieved with the data of the study basin, whereas the lower benchmark represented what could be achieved if only information of parameter value ranges was available. The model was run continuously assuming the input-data time series were available and that discharge data from only M_p events were available for calibration.

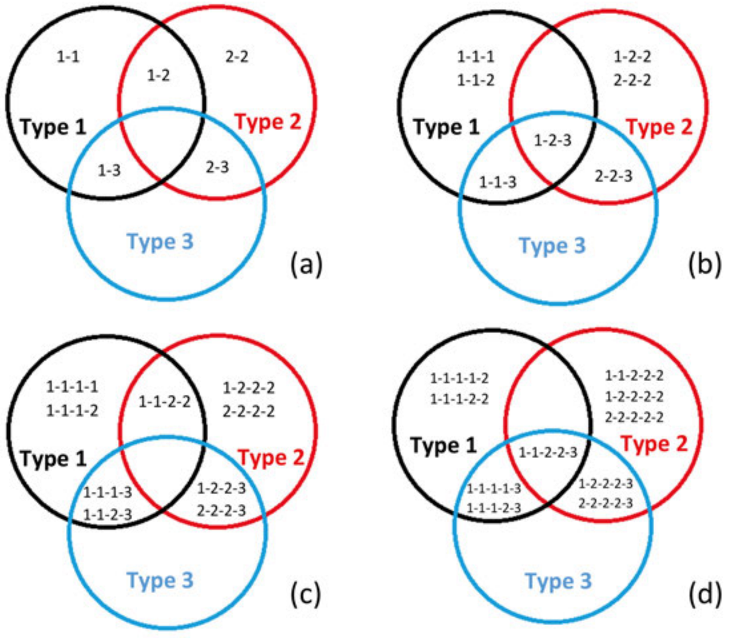

Figure 3. Classification of calibration setups, based on their event-type combination, to groups representing the information content of each type of event when M_p equals (a) two, (b) three, (c) four, and (d) five. For every M_p value, each circle represents the information content of one type of event and the serial numbers inside them indicate the event-type combinations of the calibration setups included in each group (**Paper III**).

Effects on flood predictions caused by rainfall-forecast errors

Paper IV also aimed at assessing the effects of rainfall-forecast errors on flood models calibrated on a few event hydrographs. The event combinations used in calibration were those with the events above the threshold with a small return period (i.e., 1.01 years) and the predictive ability of the calibrated parameters was further tested using several rainfall-forecast scenarios as input to the model. The rainfall forecasts were based on real-time observations but included duration and volume errors. Nine volume-error percentages were considered, each of them with nine duration-error percentages, which resulted in 81 rainfall-forecast scenarios with different degrees of uncertainty. The centre of mass of each rainfall event was used as a reference to increase and reduce their duration in both directions. The median value of accuracy obtained for all the rainfall-forecast scenarios was compared to assess the effects on flood predictions caused by uncertainties on rainfall forecasts.

Results

"We are not rich by what we possess
but what we can do without."
– Immanuel Kant

Modelling implications of the day definition

The definitions of both the climatological and discharge days had a large impact on the maximum model performance (Fig. 4). Model performance varied greatly along both axes of the climatic and discharge day definition, and changed gradually, shifting parallel to the main diagonal (Figures 4 and 5a). The highest efficiencies were found when the 24-h runoff interval lagged the 24-h rainfall interval by 2–4 h. For those cases, the model had sufficient water in storage before the largest runoff peaks had occurred, which facilitated the model to fit the observations.

Furthermore, efficiencies varied considerably along the diagonals (Fig. 5). The rainfall interval that had the greatest performance variability was 06–06. Model performance varied greatly for most of the 24-h runoff intervals, except for the intervals between 06–06 and 12–12.

Model performance for specific 24-h intervals could be explained by exploring the hourly distribution of rainfall and runoff during calibration. It was generally difficult to achieve high model performance when the climatological-day definition split the most extreme rainfall events. However, model performance varied less for some 24-h runoff intervals because the extreme runoff events were split into two, which made it less problematic to fit the observations.

If the definition of the climatological day is adequate, then model performance varies less regardless of the definition of the discharge day. The latter was confirmed by using hourly rainfall data as input to simulate daily runoff with different starting times of the day. This eliminated the effects caused by the definition of the climatological day, and as a result, those effects caused by the definition of the discharge day were almost non-existent. Hydrographs from an extreme event illustrated the behaviour of simulations with different day definitions (Fig. 6).

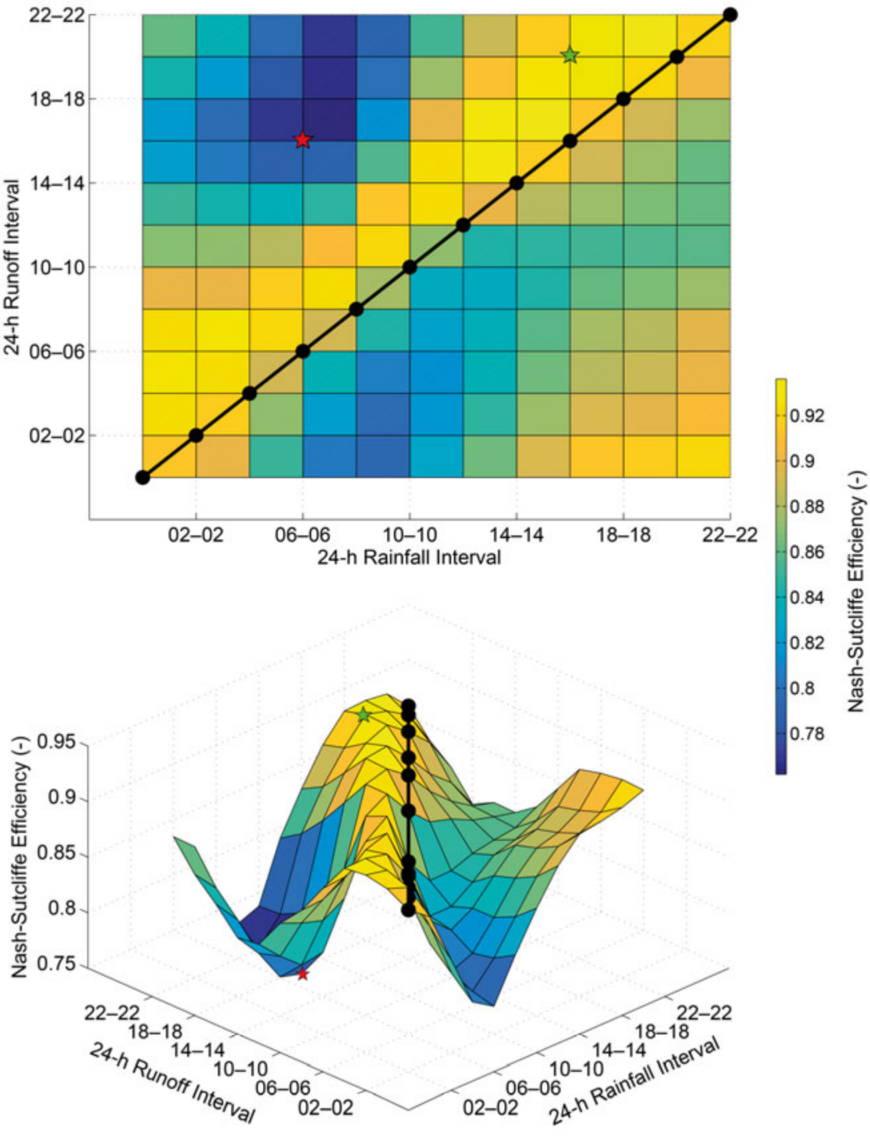

Figure 4. Two- and three-dimensional views of maximum Nash-Sutcliffe efficiencies (R_{eff}) achieved by automatic calibration (**Paper I**). The main diagonal (black line) refers to model set-ups with the same day definitions for both climatological and discharge data. The green star represents the best model set-up, whereas the red star represents the worst.

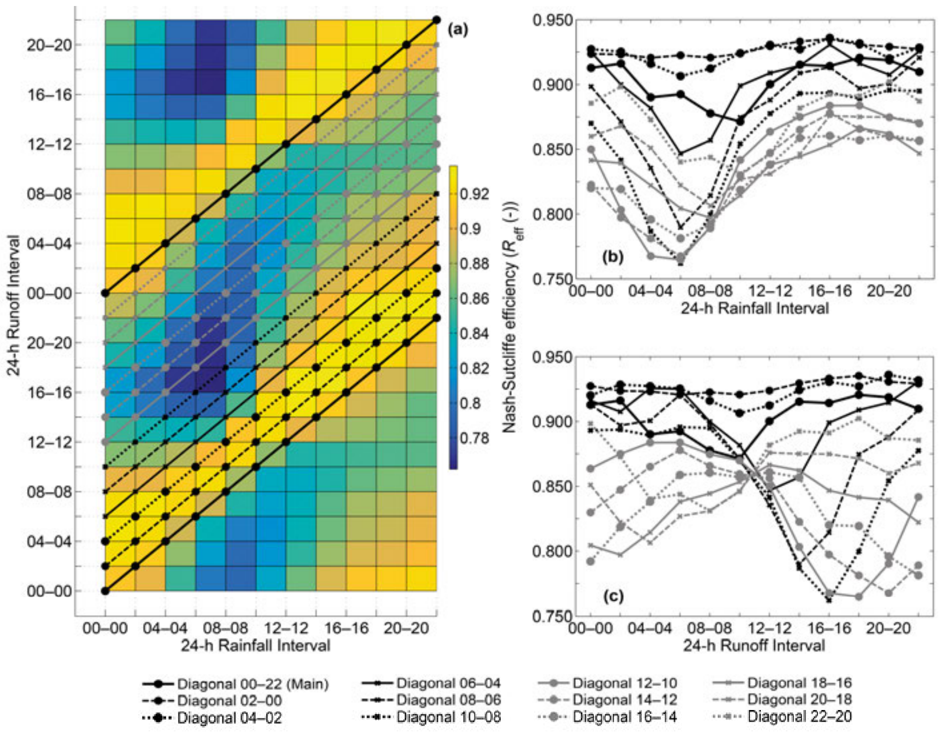

Figure 5. Maximum Nash-Sutcliffe efficiencies (R_{eff}) of every diagonal: (a) 2-D view of model performance space (same as upper panel of Fig. 4 but replicated vertically). Model performance of every diagonal along the 24-h (b) rainfall-interval axis and (c) runoff-interval axis (**Paper I**). In the legend, integer numbers of every R_{eff} diagonal refer to the 24-h runoff interval at which the diagonal starts and ends in (a) (from left to right).

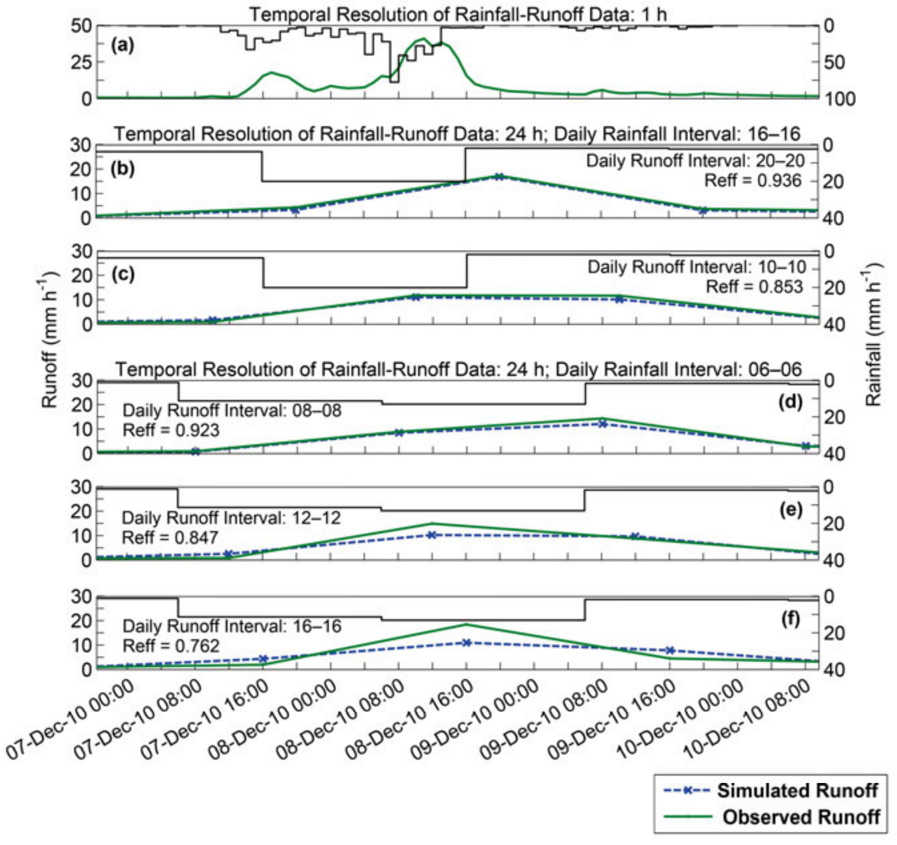

Figure 6. Hydrographs of an extreme rainfall-runoff event: (a) observed 1-h rainfall and runoff data; (b–f) daily runoff simulations for model setups with different definitions of the climatological and discharge days. Sub-plot (b) corresponds to the best model setup and (f) to the worst (**Paper I**).

Transferability of model parameters across temporal resolutions

Temporal-resolution dependencies of model parameters were almost non-existent since the value distribution of the parameters for the two basins was relatively constant across the temporal resolutions. Only a slight shift was seen when moving from sub-daily to daily on the routing-routine parameter (i.e., P_{MAXBAS}) (Fig. 7). Outliers were found for some parameters (P_{PERC}, P_{ALPHA}, P_{K1} and P_{MAXBAS}), but the percentages of them at every resolution were less than 2.2%, and they had a negligible impact on the simulated discharge bounds.

Using the parameters calibrated at the daily to simulate sub-daily runoff gave a small decrease in Nash-Sutcliffe (R_{eff}) efficiency values (Fig. 8). However, the 50th and 99th percentile R_{eff} values showed a small variation for all simulated temporal resolutions. Similarly, the use of parameters calibrated at the 3-, 6-, 12- and 24-h resolutions to simulate 1-h runoff gave some decrease in R_{eff}, but similar 50th and 99th percentile efficiencies were found irrespective of the temporal-resolution at which the parameters were calibrated.

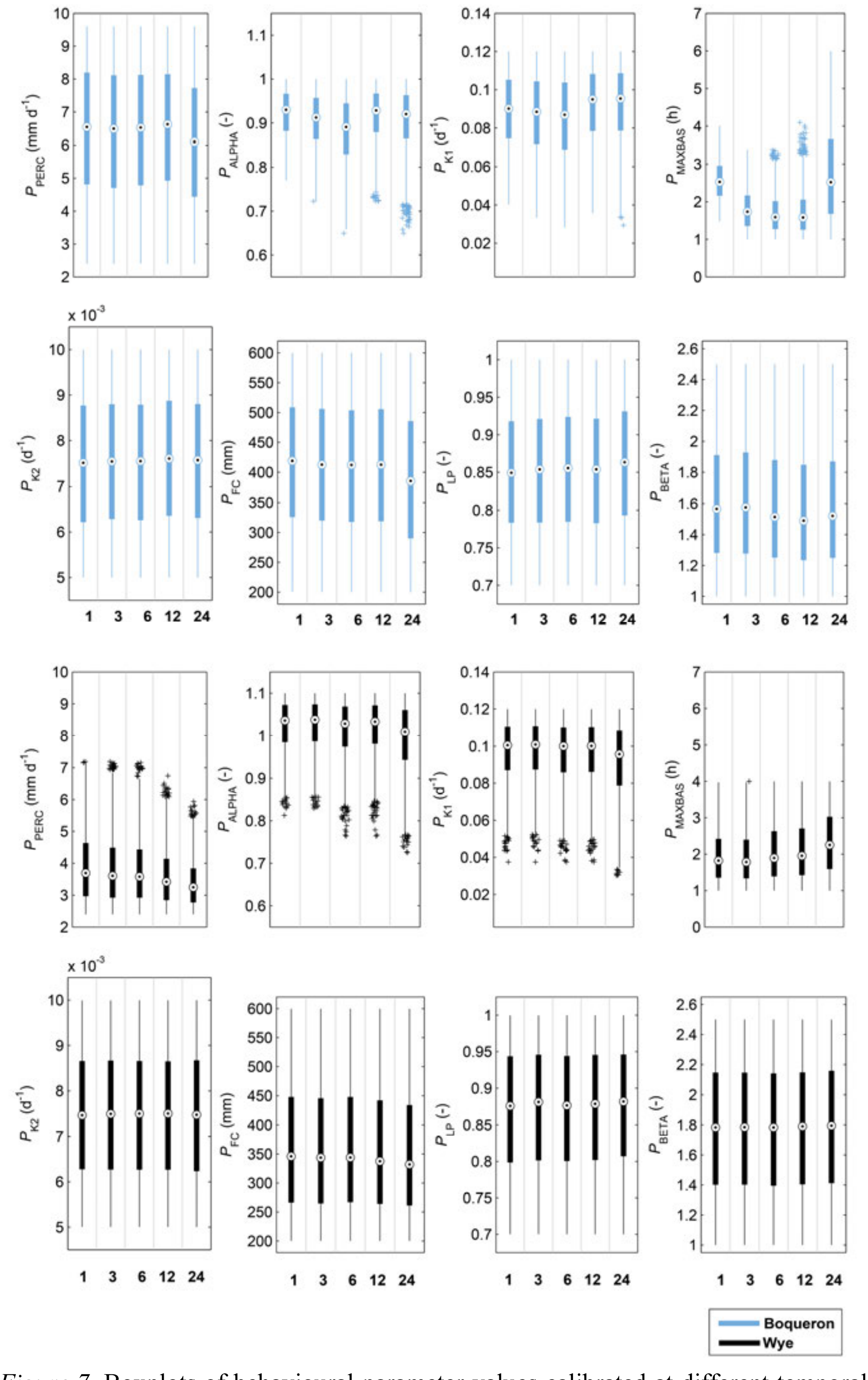

Figure 7. Boxplots of behavioural parameter values calibrated at different temporal resolutions for the Boqueron and Wye River basins (**Paper II**).

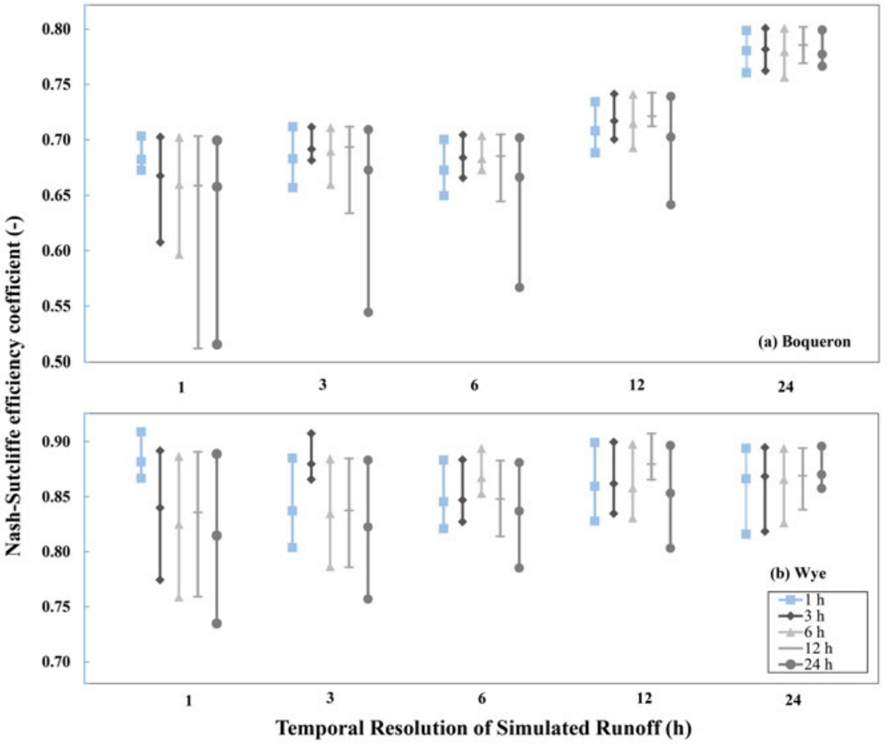

Figure 8. 1st (bottom), 50th (middle) and 99th (top) percentiles of Nash-Sutcliffe efficiency at five simulation temporal resolutions for (a) Boqueron and (b) Wye River basins when using parameters originally calibrated at five different temporal resolutions (legend in the figure) (**Paper II**).

Flood-model calibration based on limited discharge data

Calibration based on single and multiple events

In **Paper III**, the hypothesis that adequate model calibration in a data-scarce environment is possible was tested assuming that only a few event hydrographs were available for calibration. The median model performances obtained in validation were compared for every value of M_p to answer how many events are required for model calibration (Fig. 9).

The results for the joint measure $F(\Theta)$ (Fig. 9a–b) showed that when only one extreme event was used in calibration, flood predictions improved in comparison to the scenario of no data available (i.e., all values were above the lower benchmark). Having at least two events available seemed sufficient in terms of the median value of accuracy for $F(\Theta)$, since it did not always improve for M_p values greater than two. However, the uncertainty ranges of $F(\Theta)$ reduced considerably for a greater number of events. The latter was clearly seen when moving from the scenario of having only one event available to the scenario of having four events. For M_p values higher than four, no performance improvement was seen.

Furthermore, median model performances in validation were compared for each value of M_p based on the types of events used in calibration to assess how informative individual extreme events are (**Paper III**). Similarly, flood predictions improved when at least one event was available for calibration regardless of the event type (Fig. 10a). When $M_p = 3$, uncertainty ranges for all objective functions, except for $F_1(\Theta)$, were relatively similar for the three types of events but with different median values of accuracy (Fig. 10i–l). For $M_p > 3$, median values of accuracy and uncertainty ranges were relatively similar for any type of event used in calibration (Fig. 10m–t). These results suggest that when less than three events are available, the type of event matters in calibration, whereas for a greater number of events, the type of event influences prediction performance less and becomes less important.

Based on the previous findings, two sets of event combinations of three event hydrographs above thresholds with different frequency of occurrence were generated, calibrated and tested in forecasting to assess if hydrographs above a threshold with a small return period can be useful in calibration and for predicting floods (**Paper IV**). Model-performance results obtained for the two sets of event combinations (Fig. 11) showed relatively similar predictability of floods. Regardless of the frequency of occurrence of the thresholds, having three events hydrographs improved predictability in comparison to the scenario of no data available at all. This was because model performance of all the measures, except for V_E, was typically above the lower benchmarks. On average, about 3% of the events combinations based on the threshold with a low frequency of occurrence returned model performances below the lower benchmarks, whereas this number increased to 12% for the event combinations based on the threshold with a small return period. Nevertheless, the differences between model performance of the two sets seem to be acceptably small.

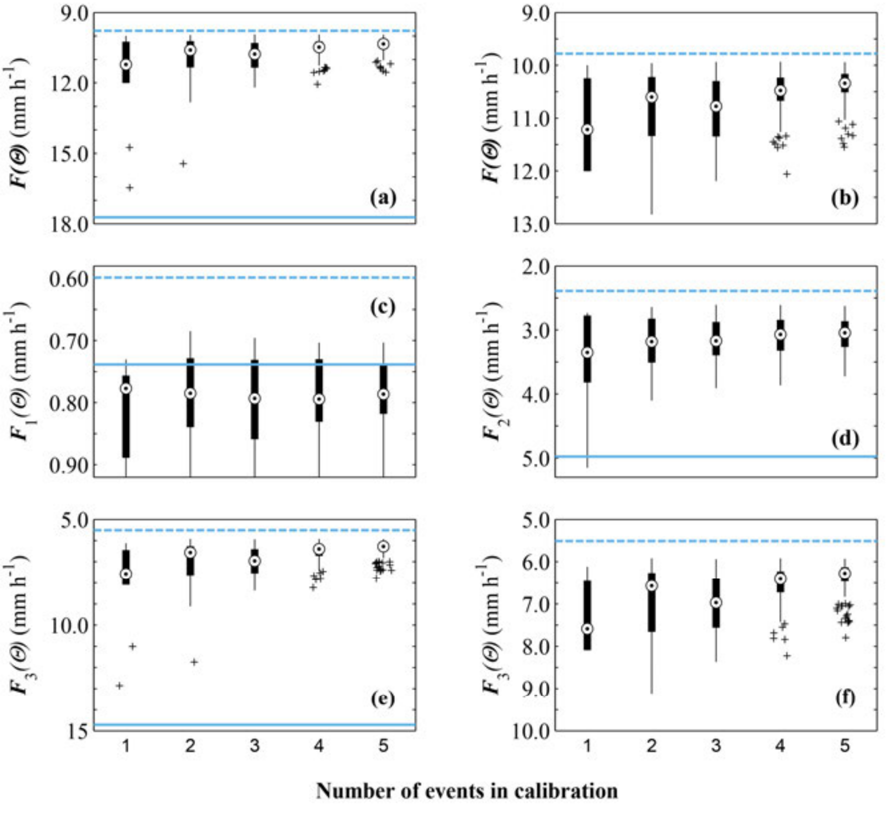

Figure 9. Boxplots of median performance in validation for different scenarios of data availability (**Paper III**). The blue dashed lines represent the upper benchmarks, whereas the blue solid lines represent the lower benchmarks; (b) and (f) are zoom-ins of (a) and (e), respectively. Upper and lower benchmarks of $F_1(\Theta)$ would be the equivalent of relative volume errors equal to 13% and 15% respectively; upper and lower benchmarks of $F_2(\Theta)$ would be the equivalent of Nash-Sutcliffe efficiencies equal to 0.90 and 0.45 respectively; whereas upper and lower benchmarks of $F_3(\Theta)$ would be the equivalent of relative error of peak flow equal to 22% and 56% respectively.

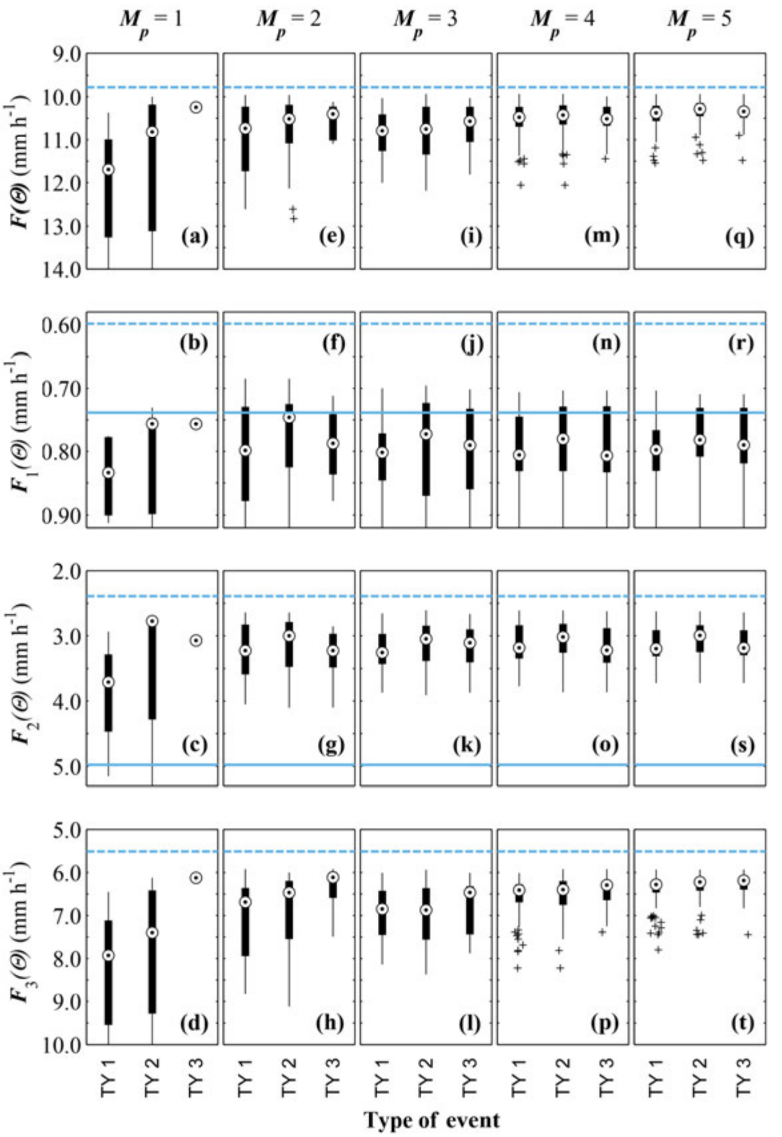

Figure 10. Boxplots of median performance in validation for different scenarios of data availability based on the type of the events used in calibration (**Paper III**). The blue dashed lines represent the upper benchmarks, whereas the blue solid lines represent the lower benchmarks. Lower benchmarks of $F(\Theta)$ and $F_3(\Theta)$ were equal to 17.7 mm h^{-1} and 14.7 mm h^{-1}, respectively. Upper and lower benchmarks of $F_1(\Theta)$ would be the equivalent of relative volume errors equal to 13% and 15% respectively; upper and lower benchmarks of $F_2(\Theta)$ would be the equivalent of Nash-Sutcliffe efficiencies equal to 0.90 and 0.45 respectively; whereas upper and lower benchmarks of $F_3(\Theta)$ would be the equivalent of relative error of peak flow equal to 22% and 56% respectively.

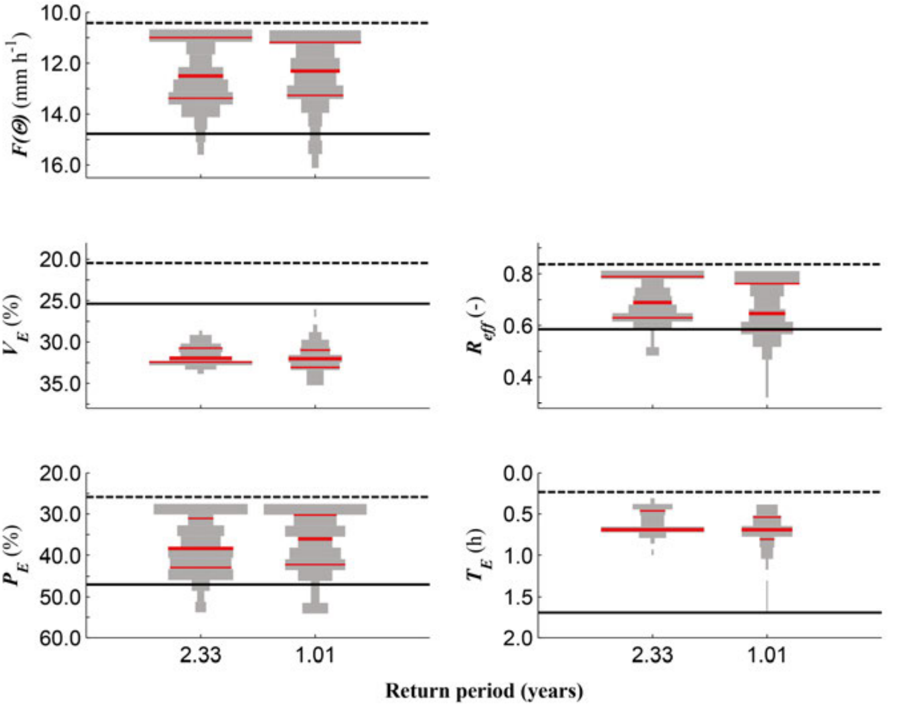

Figure 11. Histogram of median model performance in flood forecasting, visualised as violin plots, when using parameters calibrated based on three event hydrographs and when using rainfall forecast with a quality as good as that of real-time observations (**Paper IV**). The combinations of three event hydrographs were based on events above thresholds with a low (return period of 2.33 years) and a high frequency of occurrence (return period of 1.01 years). The black dashed lines represent the upper benchmarks, whereas the black solid lines represent the lower benchmarks. The red solid lines represent the 25th (top), 50th (middle) and 75th (bottom) percentiles of median model performance.

Effects on flood predictions caused by rainfall-forecast errors

Several rainfall forecast scenarios were used to test the predictive ability of a model calibrated on event combinations of three event hydrographs above the threshold with a high frequency of occurrence (return period of 1.01 years). For this, the median value of accuracy obtained for each forecast scenario was compared to investigate the effects on flood predictions caused by errors in rainfall forecasts. Model-performance results in terms of flood-peak errors and Nash-Sutcliffe efficiencies (Figures 12 and 13) show that the accuracy of the rainfall forecasts strongly influenced the predictive ability of the model. Between volume and duration errors, flood predictions were highly sensitive to the former since model performance varied greater along the vector with only rainfall-volume errors than along the vector with only duration errors. Model performance concerning time-to-peak errors was only sensitive to rainfall-duration errors, whereas model performance regarding flood-volume errors was only sensitive to rainfall-volume errors.

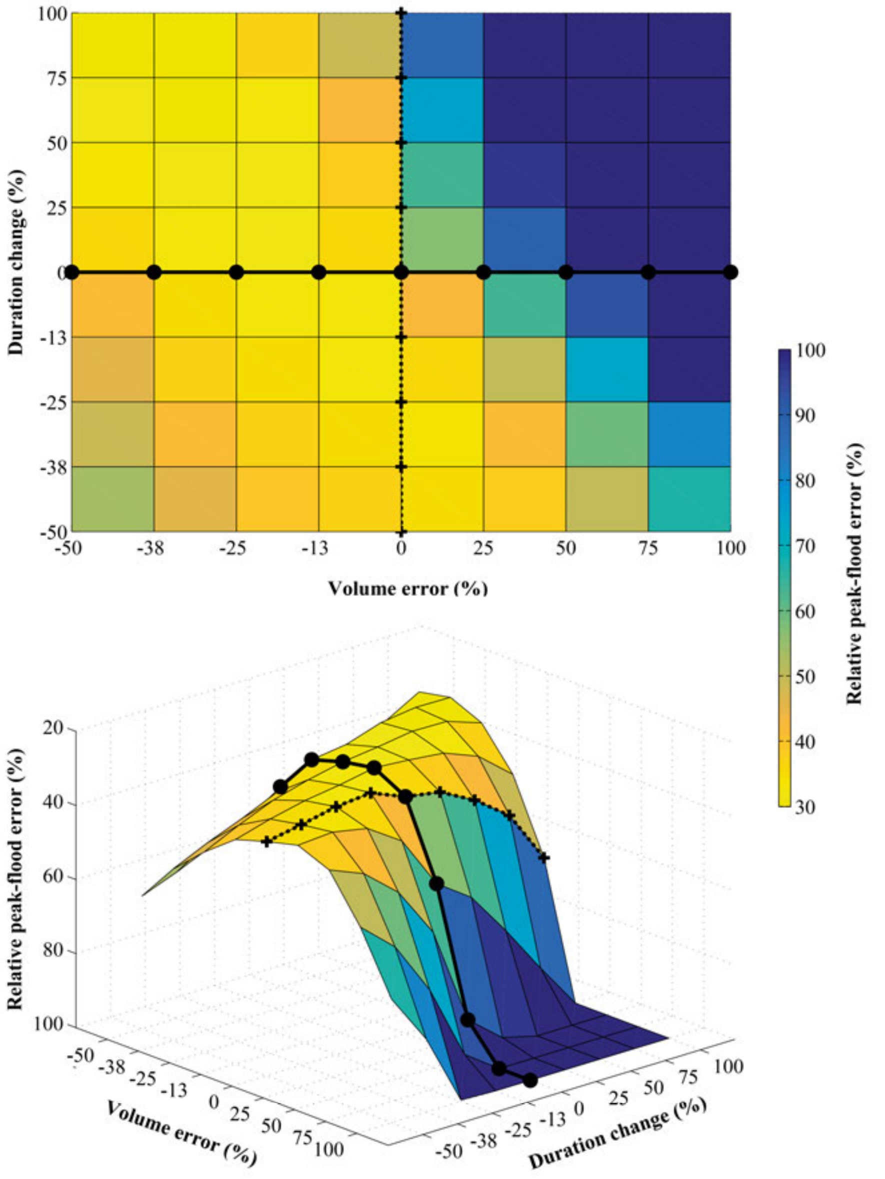

Figure 12. Two- and three-dimensional views of the median value of accuracy of peak-flood errors for several rainfall-forecast scenarios (**Paper IV**). A relative peak-flood error of 0% corresponds to a perfect fit and values increase with decreasing performances. The black solid line represents the vector of rainfall forecasts with only rainfall-volume errors, whereas the black dotted line represents the vector with only rainfall-duration errors.

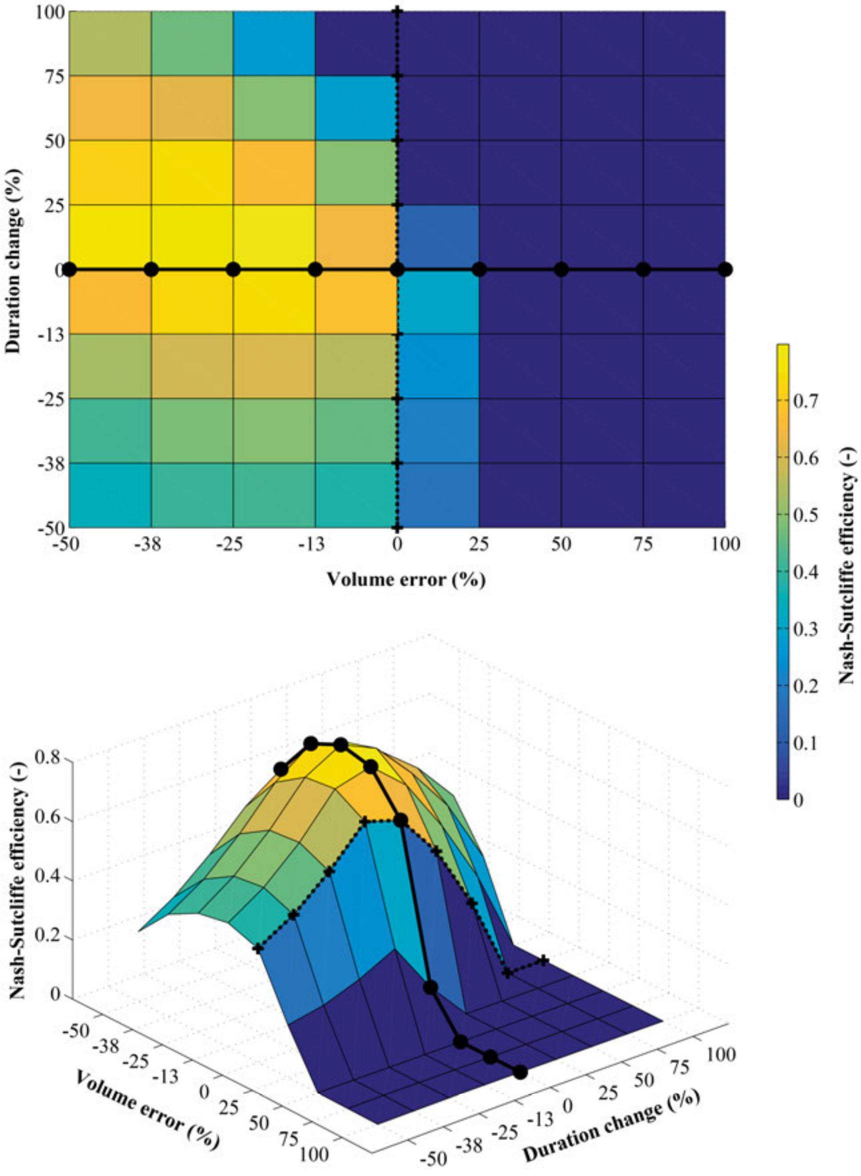

Figure 13. Two- and three-dimensional views of the median value of accuracy of Nash-Sutcliffe (R_{eff}) efficiencies for several rainfall-forecast scenarios (**Paper IV**). A R_{eff} value of 1 corresponds to a perfect fit. An efficiency of 0 means that simulation is as accurate as the mean of the observed data, whereas an efficiency less than zero (R_{eff} < 0) means that the observed mean is a better predictor than the model. The black solid line represents the vector of rainfall forecasts with only rainfall-volume errors, whereas the black dotted line represents the vector with only rainfall-duration errors.

Discussion

"It always seems impossible until it's done"
–Nelson Mandela

The purpose of this thesis was to enhance water resources and flood management in data-scarce basins by maximising the value of limited hydro-meteorological data. This was done in several steps by improving the understanding of the effects on hydrological models caused by data-related uncertainties and by developing methods to improve the robustness of runoff- and flood-model calibration.

Hydro-meteorological data at sub-daily resolutions have increasingly become available (Girons Lopez & Seibert, 2016) but daily data are still most common. These data often come from hydro-meteorological offices with limited information on quality and uncertainties. The definitions of the climatological and discharge days are seldom available or presented when data are used for hydrological modelling.

Results in **Paper I** showed that the definition of the climatological and discharge days had large implications on model calibration and runoff simulation. Model performance was more dependent on the definition of the climatological day than on the definition of the discharge day. When a storm overlapped two daily observations because of the climatological-day definition, rainfall intensities were reduced and accurate hydrograph predictions were then only possible if most of the rainfall event had entered the hydrological system before the occurrence of the largest discharge peaks. It was assumed that the main reason for performance differences was the effect of how storm water (1-h observations) was assigned to one or more daily rainfall values. If the climatological day is poorly defined, the way continuous runoff records are assigned to daily runoff values will determine how well a model fits observations.

The definitions of the climatological and discharge days are a data-related uncertainty. Given that uncertainty of the data considerably affects models in calibration, it was assumed that the definitions of the climatological and discharge days of the data are as important and influential in hydrological modelling as other widely investigated sources of uncertainty. In daily modelling applications, the effects of the definition of day are likely to be more pronounced if basin responses occur at time scales finer than daily and should therefore be presented.

The need of flood-forecasting models at sub-daily temporal resolutions and the lack of data at these resolutions for calibration motivate exploring methods where parameter sets calibrated at low temporal resolutions can be used to simulate runoff at high temporal resolutions. Results of **Paper II** showed that model-parameter dependencies on the temporal resolution of data were almost non-existent when the explicit Euler method was run with a modelling time-step of 1 h. This means that parameters calibrated at one temporal resolution could be used at other without time scaling. This result supports the argument that robust numerical integration reduces parameter temporal-resolution dependence (Kavetski *et al*., 2011; Santos *et al*., 2018).

In the literature, it is argued that model parameters become temporal-resolution independent when the temporal resolution of the rainfall-runoff data used for calibration approaches zero (Littlewood & Croke, 2008), whereas the results in **Paper II** support the idea that parameters become independent of the temporal resolution of data when the modelling time-step is sufficiently small but larger than zero. By separating modelling time-step from the temporal resolution of the data, it was possible to study data temporal-resolution dependencies free from numerical errors that could otherwise corrupt sensitivity analyses, model calibration, result interpretation and model uncertainty analyses (Kavetski & Clark, 2011; Kavetski *et al*., 2011; Michel *et al*., 2003).

The cross-temporal-resolution comparison in **Paper II** showed a performance decrease of R_{eff} when parameter sets calibrated at lower temporal resolutions than 1 h were used to model at this temporal resolution. The latter could have been because parameter information content was too limited at lower temporal resolutions than 1 h. When parameter sets calibrated at the daily were used to simulate runoff at sub-daily resolutions, R_{eff} decreased only slightly in comparison to when parameter sets calibrated at those temporal resolutions were used. This slight decrease in performance may have been caused by the low sensitivity of the routing parameter at the daily.

Knowing the value of small amounts of data for model calibration is essential in data-scarce conditions. **Paper III** hypothesised that adequate model calibration in a data-scarce environment is possible when hydrographs of only a few events are available. Results of **Paper III** suggest that continuous observations from at least two events may be sufficient to calibrate a model for flood prediction. While increasing the number of calibration events leads to an increased performance and reduced uncertainty, the effect seems to level off already after four calibration events. This strengthens the argument that calibration-data needs rely on the information content in the observations rather than on the pure number of individual observations. Moreover, continuous measurements of individual events may provide sufficient information for constraining model parameters (Seibert & McDonnell, 2013), meaning that fewer calibration data might be necessary if data are taken in an event-based way (McIntyre & Wheater, 2004).

Individual extreme events can contain a lot of information but it depends on the scenario of data availability, how informative they are. When the number of events used for calibration was equal or greater than three, it seemed that the information content of individual events became relatively equal and less influential in the predictions, regardless of the characteristics and magnitude of them (**Paper III**). By calibrating the model using multiple events at once, it is assumed that parameter sets chosen as behavioural include sufficient information to predict different types of events and not just one type as it happened when one or two events were used.

Overall, results in **Paper III** showed that using few event hydrographs in calibration improves flood predictions in comparison to the scenario of no discharge data. However, this study was based on the assumption that the discharge time series of floods were recorded and available for calibration. In practice, measuring those events is difficult because their probability of occurrence is low and it is not known in advance when they will occur. **Paper IV** explored the use of event hydrographs above a threshold with a high frequency of occurrence for flood-model calibration. The events used in calibration in **Paper IV** were based on two thresholds with different frequency of occurrence. Results showed relatively similar flood-prediction skills for both thresholds, although the threshold with the smallest return period resulted in a larger number of event combinations that were slightly less informative than the scenario without data. Still, close to the 90% of event combinations based on the latter events were found to be equal or more informative than when no data were available and therefore, showed to be useful for flood-model calibration and forecasting. Data needs are expected to be relative to the complexity of the basins, climate and models, as well as by the dominant flood types for each case. The basin used for **Paper III** and **IV** was a small tropical basin with a fast response dominated by rainfall floods which could explain the small data needed for improving the prediction of floods compared to the scenario of no data. Although data requirements may vary for other regions with different climatological conditions, results of the latter studies are promising for real time flood-forecasting applications in data-scarce and budget-limited conditions.

Errors in rainfall forecasts are the main source of uncertainty in flood forecasting. This limits the usability of hydrological models in operational applications (Kobold, 2007). **Paper IV** assessed the effects on flood predictions caused by rainfall-forecast errors in data-limited conditions. Results showed that flood predictions were sensitive to both volume and duration errors of the rainfall forecast. Errors of one seemed to compensate for the errors of the other since good modelling performances could be found for large errors of both. At the same time, the interplay between the two errors was found too complex. The sensitivity analysis results are expected to be useful for improving the accuracy of rainfall forecasts with a focus on rainfall-runoff models and, ultimately, for obtaining meaningful flood forecasts.

Conclusions

This thesis deals with issues related to the scarcity and lack of high temporal-resolution hydro-meteorological data for flood-forecasting applications and explores methods to address these limitations. More specifically, the main contributions are:

- I The assessment of the effects caused by the definition of the day on hydrological models. **Paper I** showed that the definition of the climatological and discharge days had large implications on model calibration, runoff simulation and might influence regionalisation and flood-forecasting applications.
- II A methodology to treat empirically model-parameter dependencies on the temporal resolution of data using a bucket-type hydrological model. Results in **Paper II** showed that parameters become independent of the temporal resolution of data when the modelling time-step is sufficiently small. This implies that if sub-daily forcing data can be secured, flood forecasting in basins with sub-daily concentration times may be possible with model-parameter values calibrated from time series of daily data.
- III A methodology for improving the robustness of flood-model calibration using limited discharge data. **Paper III** showed that by using few event hydrographs in calibration, the predictability of floods improved in comparison to the scenario of no data available. Two event hydrographs may be sufficient for calibration, but accuracy and reduction in uncertainty may improve if more events can be made available. Moreover, it was shown that the information content of individual events was relatively equal when three or more events were used in calibration. **Paper IV** showed that using events above a threshold with a small return period in calibration may be as useful for predicting floods as using only extreme events with a low frequency of occurrence.
- IV The assessment of the effects of rainfall-forecast errors on a flood model calibrated in data-scarce conditions. Results of **Paper IV** showed that flood predictions were sensitive to volume and duration errors of the rainfall forecasts, but the former had

the larger impact on model performance. Calibrating a model with a limited number of events proved to be also useful for predicting floods given uncertain rainfall forecasts.

Limited hydro-meteorological data offer opportunities for predicting floods in data-scarce conditions by improving knowledge and methodology of flood-management practices. By maximising the value of such data, the methods presented in this thesis proved to be useful for predicting floods and are expected to enhance water-resources and flood management, and ultimately, reduce the detrimental effects of floods, in terms of economic and human life losses, in data-poor regions.

Finally, it must be emphasised that the methods proposed in this thesis were limited to one–two basins and one model. The generality of the results can only be proven when the methods here included are tested on other models and basins where other hydrological processes dominate.

Acknowledgements

"Luck is when opportunity knocks and you answer."
–Anonymous Author

To start, I would like to say that I consider myself a very lucky person for having the opportunity to move and study in Sweden. One person I should thank for making that possible is **Sven Halldin**. Since I arrived in Sweden, you have always supported me with your guidance and advice as my main supervisor. You always encouraged me and highlighted my PhD milestones, even when I didn't see them. I am very thankful for that, for everything you taught me and for your patience during my time as a PhD student. **Chong-Yu Xu**, thank you for the advice and help you gave me all these years. Your positive attitude and contagious sense of humor was a bright spot in all our meetings, even in difficult and stressful times in my PhD, thank you so much for that**. Jan Seibert**, thank for you for the advice, creative ideas, insightful one-to-one meetings, and for being there for when I had difficulties with the model. **Thomas Grabs**, you joined my group of supervisors in the late stages of my PhD but you made a significant contribution in my work since then. Thank you for that, for the constructive comments and for being available when I had questions. I was very lucky to have you all as supervisors, I always liked our dynamics in meetings, which certainly were beneficial for my progress and development during my PhD. Really, thank you all for the help! I wouldn't have made it without any of you.

Thanks to **Anna Kauffeldt** for helping me in sharpening my first publication. **Diana Fuentes** and **Beatriz Quesada**, thank you for sharing ideas and interesting discussions. Thanks to **Lebing Gong** and **José Luis Guerrero** for helping me in my early stages of programming in MATLAB. Thanks to **Giuliano Di Baldassarre**, even when you were not one of my supervisors, you were always available for spontaneous meetings when I had questions. I would like to thanks **Lucia Gutiérrez**, **Kristina Conrady**, **Chiara Költringer**, **Sergey Marchenko** and **Yunus Baykal** for letting me use their computers to carry out some of the experiments needed to complete my PhD.

This research couldn't have been possible without the **CNDS** research school, supported by the **Swedish International Development Cooperation Agency**

(Sida) through their agreement with **International Science Programme** (ISP) at Uppsala University (contract number: 54100006). Thanks to the publishers, **Elsevier** and **Taylor & Francis**, for their kind permission to reprint material from the publications of Papers I and II.

Thanks to the **Panama Canal Authority** (ACP) and the **Department of Hydrometeorology** at Empresa de Transmisión Eléctrica, S.A. (ETESA) who provided part of the data used in this research. I would also like to thanks **Juan Antonio Gomez** and **Elias López** for hosting me at the University of Panama in my visits to Panama during my PhD studies.

Many thanks to the staff at **ISP** for taking care of my family and me since we arrived in Sweden. I would also like to thank my current and former **colleagues at the department**, who made my PhD life a fun and unforgettable experience. Thank you so much for all the chats, the fikas, the breaks and the time you shared with me during my time as a PhD student.

This was also possible thanks to my family. A ti **Nilsa**, que siempre me has apoyado, acompañado y dado aliento durante todo el doctorado. Sin ti la incertidumbre de los parámetros no hubiese sido la misma. Gracias por apoyarme desde el inicio en esta aventura. Este logro es tanto tuyo como mío. A mi **Isabella**, que sin importar el humor en que estuviera, siempre encontraba la forma de hacerme sonreír y de alegrarme el día después de algún día difícil en la universidad. Tú y tu mamá eran mi escape del doctorado. A mi madre, **Clelia**, por su apoyo incondicional y por todos los sacrificios que hizo para que yo sea la persona que soy ahora. A mi hermana, **Joyce**, por siempre estar ahí para mi aun en la distancia. A ti **Aneth**, sino fuera por ti, no me hubiese enterado de la convocatoria para estudiar en Suecia y me hubiese perdido de esta gran experiencia. A **Nelson** y **Aracelly** por siempre apoyarme y hacerme sentir parte de la familia. Finally, I would like to thank my friends in Panama and Sweden for being there for me and for their support during my PhD studies.

Thank you all!

Sammanfattning på svenska (summary in Swedish)

Högflödesprognoser i avrinningsområden med bristfällig information. Maximering av värdet av begränsade hydrometeorologiska data

Översvämningar är ett samhällshot och ibland en naturkatastrof med förluster av människoliv och omfattande materiella skador på många ställen i världen. Översvämningar kan bli speciellt allvarliga i låginkomstländer beroende på deras sårbarhet och att höga flöden är vanligt förekommande. Översvämningsprognoser kräver modellsimuleringar av höga flöden med högre tidsupplösning än dygn i avrinningsområden där svarstiden understiger 24 h. Användning av sådana modeller beror på tillgång av inomdygnsdata, något som det ofta är brist på eller som saknas helt. Det är inte alltid möjligt att modellera på traditionellt sätt med den tidsupplösning som krävs, något som tvingar hydrologer att göra det bästa möjliga av de data som finns. Bristen på hydrometeorologiska data försvårar översvämningsberäkningar med hydrologiska modeller, men är samtidigt en drivkraft för att förbättra kunskapsläget och hanteringen av översvämningsrisker.

Det övergripande målet med denna avhandling var att förbättra förvaltningen av vattenresurser och hanteringen av höga flöden i avrinningsområden med begränsad hydrologisk information och med svarstider mindre än dygn. Målet har uppnåtts genom att förverkliga två delmål: (1) förbättra förståelsen av datarelaterade osäkerheter i hydrologisk modellering (uppsatserna I, II och IV), (2) utveckla metoder för att göra kalibreringen av avrinnings- och högflödesmodeller mer robust när hydrometeorologiska data är begränsande (uppsatserna II, III och IV). Arbetet har fokuserat på Mellanamerika och omfattar fyra studier i lokal skala i regionen.

Hydrologiska modeller påverkas av osäkerheter i väder- och vattenföringsdata. Även om flera osäkerheter har studerats ingående, har inverkan av olika starttider på observationsdygnet (dygnsdefinitionen) nästan helt lyst med sin frånvaro. Avhandlingens första uppsats undersökte effekterna av definitionerna av det klimatologiska dygnet och vattenföringsdygnet på en nederbördsavrinningsmodell. Genom att variera dygnsdefinitionerna för väder- och vattenföringsdata visades att denna dataosäkerhet hade stor påverkan på modellkalibrering och simulering av vattenföring. Därigenom påverkades regionalisering och beräkning av höga flöden. Den klimatologiska dygnsdefinitionen påverkade modellens beräkningsförmåga mer än avrinningens dygnsdefinition. Regnintensiteten reducerades när ett regntillfälle ingick i två dygnsobservationer och noggranna högflödesberäkningar var bara möjliga när merparten av allt regn hade fallit före den största högflödestoppen. Huvudorsaken till skillnaderna i modellens beräkningsförmåga berodde på hur ett givet högflöde (1-h observationer) fördelades på en eller flera dygnsregn.

Parametervärden som kalibrerats mot data med olika tidsupplösning har visat sig variera påtagligt beroende på tidsupplösningen. Orsakerna till dessa beroenden har hänförts till förlusten av information om fysiska processer när data har medelvärdesbildats till en lägre tidsupplösning. I uppsats II utvecklades en metod för att empiriskt hantera tidsberoendet hos en modells parametervärden på grundval av datas tidsupplösning. Parametervärderna blev oberoende av tidsupplösningen hos data när modellens numeriska tidssteg vid explicit Eulerintegrering sattes till en timma oavsett tidsupplösning på indata och kalibreringsdata. Angreppssättets enkelhet möjliggjorde en praktisk och tillräckligt robust integrering som begränsade parametervärdenas beroende av tidsupplösningen hos data. Genom att skilja modellens tidssteg från tidsupplösningen hos data var det möjligt att studera modellens beroende av datas tidsupplösning utan koppling till numeriska fel. Resultatet innebär att, om man kan få fram drivdata med inomdygnsupplösning, är det möjligt att göra högflödesprognoser i avrinningsområden med svarstider mindre än ett dygn genom att kalibrera modellen mot tidsserier av dygnsdata. Studien visade i korthet att parametervärden kalibrerade med låg tidsupplösning kan vara värdefulla för att göra högflödesprognoser med hög tidsupplösning.

Eftersom det kräver stora resurser att anlägga vattenföringsstationer kan ett alternativ vara att i stället mäta vattenföringen vid ett begränsat antal högflödestoppar. Uppsats III prövade hypotesen att det är möjligt att få en godtagbar kalibrering när det råder brist på vattenföringsdata om man kan få tillgång till vattenföringen vid ett fåtal högflöden. Värdet av sådana data utvärderades utifrån kvantitet och informationsinnehåll. En ny kalibreringsmetod utvecklades för att göra högflödesprognoser mer robusta på grundval av ett fåtal vattenföringsobservationer vid högflöde jämfört med inga observationer alls. Metoden använde kalibrering vid ett begränsat antal högflöden men tog hänsyn till en tidsserie som omfattade alla tillgängliga högflöden för att välja ut de parametervärdesuppsättningar som gav godtagbara (behavioural) resultat. Utvärderingen av högflödesberäkningar grundade på utvalda parametervärdesuppsättningar visade att två högflödesobservationer kan räcka för kalibrering men att beräkningens noggrannhet ökar och dess osäkerhet minskar om fler observationstillfällen kan göras tillgängliga. Angreppssättet förbättrade högflödesprognoser jämfört med en situation där vattenföringsdata helt saknades. För fler än tre observationstillfällen blev prognosen mindre beroende av de enskilda observationernas informationsvärde, d.v.s. flödestopparnas karaktäristik och storlek påverkade prognosen i begränsad omfattning.

Flödestopparna som användes för kalibrering i uppsats III var de högsta tillgängliga. Förekomsten av sådana toppar är svåra att förutse och det är därför mindre troligt att man lyckas mäta vattenföringen i fält just när de högsta topparna inträffar. Uppsats IV provade kalibreringsmetoden från uppsats III vid högflöden större än ett tröskelvärde som ofta överskrids. Sådana högflöden visade sig vara lika användbara för kalibrering som de allra högsta, och sällan förekommande högflödestopparna. Resultaten i uppsatserna III och IV tyder på att ett begränsat antal flödestoppar, observerade med hög tidsupplösning, räcker för modellkalibrering då de innehåller tillräckligt med information för att avgränsa parametervärdesrummet. En begränsad observationsmängd visade sig också värdefull för att förstå avrinningsområdets gensvar för att förbättra högflödesprognoser i avrinningsområden med begränsade data.

Hydrologiska modeller kopplade till regnprognoser kan användas för att varna för höga flöden i avrinningsområden med korta svarstider. Samtidigt påverkar de ofta stora felen i regnprognoser förmågan hos hydrologiska modeller att förutsäga höga flöden tillräckligt bra. I uppsats IV presenteras en känslighetsanalys som utvärderar påverkan av osäkerhet i regnprognoser på beräkningar av höga flöden i en nederbörds-avrinningsmodell som kalibrerats mot ett begränsat antal höga flödestoppar. I studien användes olika scenarier för regntillfällen grundade på verkliga regnobservationer men där olika volyms- och varaktighetsfel lagts till. Regnen användes som drivdata till en modell för att beräkna höga flöden. Resultaten visade att högflödesprognoserna var känsliga för båda sortens fel i regnprognoserna, men att volymfelen hade störst påverkan på modellresultaten. Volymfel kunde kompensera för varaktighetsfel så att bra simuleringsresultat kunde erhållas för stora fel av båda slagen. Sammantaget visade sig modellkalibrering mot ett begränsat antal högflödestillfällen vara användbar även vid prognoser som grundades på osäkra regnprognoser. Resultaten av känslighetsanalysen kan användas för att förbättra regnprognoser med inriktning mot förbättrade nederbörds-vattenföringsmodeller och ytterst för att få bra prognoser för höga flöden och översvämningar.

Tillgången till hydrometeorologiska data är central för hantering av översvämningsrisker. Metoderna som beskrivs i denna avhandling visar värdet av begränsade hydrometeorologiska data och kan vara användbara för att förutsäga höga flöden. Arbetena som presenteras i avhandlingen syftar till att höja medvetenheten om värdet av begränsade hydrometeorologiska data och förväntas bidra till en bättre hantering av översvämningsrisker vid förvaltning av vattenresurser och ytterst att begränsa översvämningsskador vid höga flöden i områden där tillgången på vattenföringsdata är begränsad eller där data helt saknas.

Slutligen måste sägas att metoderna som presenteras i avhandlingen bara har provats och utvecklats i en eller två avrinningsområden och med hjälp av en hydrologisk modell. Resultatens allmängiltighet kan bara säkerställas om metoderna provas med andra modeller och i avrinningsområden där andra hydrologiska processer dominerar jämfört med dem i Mellanamerika.

Resumen en español (summary in Spanish)

Pronósticos de inundaciones en cuencas hidrográficas con escasez de datos. Maximizando el valor de datos hidro-meteorológicos limitados.

Las inundaciones son una amenaza para la sociedad que puede resultar en pérdida de vidas humanas y en grandes daños materiales en muchos lugares del mundo. Las inundaciones pueden ser particularmente graves en países de bajos ingresos debido a su vulnerabilidad a la ocurrencia de estos fenómenos naturales. En cuencas hidrográficas con tiempo de concentración inferior a 24 h se necesitan modelos que pronostiquen inundaciones con una resolución temporal superior al día. El uso de dichos modelos depende de la disponibilidad de datos hidro-meteorológicos a escalas sub-diarias, que a menudo no están disponibles o no existen. Modelar con datos a la resolución temporal requerida no siempre es posible, lo que deja a los hidrólogos solo con la opción de aprovechar al máximo los datos disponibles. La falta de datos hidro-meteorológicos complica los pronósticos de inundación con modelos hidrológicos, pero al mismo tiempo ofrece oportunidades para mejorar el conocimiento científico y la gestión del riesgo de inundaciones.

El objetivo general de esta tesis fue mejorar la gestión de los recursos hídricos y del riesgo de inundaciones en cuencas con información hidrológica limitada y tiempo de concentración inferior a 24 horas. Dicho objetivo se logró mediante la ejecución de dos sub-objetivos: (1) mejorar la comprensión del impacto en el modelado hidrológico causado por incertidumbres relacionadas a los datos (ensayos I, II y IV), (2) desarrollar métodos para mejorar la robustez en la calibración de modelos de escorrentía y en modelos de inundación cuando los datos hidro-meteorológicos son limitados (ensayos II, III y IV). La tesis se centra en América Central e incluye cuatro estudios ejecutados en la escala local.

Los modelos hidrológicos se ven afectados por incertidumbres relacionados a los datos del clima y de caudal. Aunque los efectos causados por varias de estas incertidumbres han sido estudiados a profundidad, el impacto causado por la hora de inicio del día en las observaciones (la definición del día) ha recibido poco interés. El primer ensayo de la tesis investigó los efectos causados por la definición del día de los datos del clima y de caudal en un modelo de lluvia escorrentía. Al variar la definición del día de los datos se

demostró que esta incertidumbre relacionada a los datos tuvo un gran impacto en la calibración del modelo y en las simulaciones de caudal. Esto podría tener consecuencias en la regionalización de parámetros hidrológicos. La definición del día en los datos climatológicos tuvo un mayor efecto en el desempeño del modelo que la definición del día en los datos de caudal. La intensidad de la lluvia disminuyó cuando una tormenta traslapaba dos observaciones diarias, y solo fue posible obtener predicciones precisas del hidrograma si la mayor parte de la lluvia ya había entrado al modelo para cuando ocurría el pico más alto de caudal. La razón principal de las diferencias en el desempeño del modelo fue causada por cómo se distribuyó la lluvia horaria observada en uno o más valores diarios.

En la literatura, los valores de los parámetros calibrados en diferentes resoluciones temporales se han mostrado que varían considerablemente y que dependen de la resolución temporal de los datos. Las causas de estas dependencias se han atribuido a la pérdida de información de los procesos físicos a medida que los datos se agregan o promedian en resoluciones temporales más bajas que en las cuales estas ocurren. En el ensayo II, un método se desarrolló para gestionar empíricamente la dependencia de los parámetros con respecto a la resolución temporal de los datos. Los valores de los parámetros se volvieron independientes de la resolución temporal de los datos cuando la solución numérica del modelo, el método explicito, se configuró en pasos de tiempo de una hora, independientemente de la resolución temporal de los datos de entrada y de calibración. La simplicidad del método produjo una integración práctica y suficientemente robusta, que redujo la dependencia de los parámetros con respecto a la resolución temporal de los datos. Al distinguir el paso de tiempo del modelo de la resolución temporal de los datos, fue posible estudiar la dependencia de los parámetros con respecto a la resolución temporal de los datos sin vincularlos a errores numéricos. Como resultado, si se pudiesen obtener datos de entrada en resoluciones temporales sub-diarias, sería posible hacer pronósticos de inundación en cuencas con tiempo de concentración menor a un día usando parámetros calibrados con series de tiempo de datos diarios. El estudio demostró que los parámetros calibrados en resoluciones temporales bajas podrían ser de valor para predecir inundaciones en resoluciones temporales más altas.

Dado que el establecimiento y mantenimiento de una estación de caudal permanente requiere de grandes recursos, una solución alternativa podría ser medir el caudal en un número limitado de crecidas. El ensayo III puso a prueba la hipótesis de que es posible obtener una calibración aceptable en condiciones de escasez de datos cuando se dispone de unos cuantos hidrogramas de crecidas. El valor de dichos datos se evaluó en términos de cantidad y contenido de información. Se desarrolló un nuevo método de calibración basado en pocos datos de caudal para hacer pronósticos de inundaciones más robustos en comparación con el escenario de ninguna observación en absoluto. La calibración del método fue en función de cada evento, pero tomó en consideración los datos de todos los eventos disponibles como uno sola serie de tiempo para seleccionar los conjuntos de parámetros que dieron resultados aceptables. La evaluación de los pronósticos de inundación mostró que dos hidrogramas de crecidas podrían ser suficiente para calibrar un modelo, pero la precisión de las predicciones aumenta y sus incertidumbres disminuyen si se pueden disponer de datos de un mayor número de eventos. La técnica mejoró los pronósticos de inundación en comparación con el escenario sin datos de caudal. Cuando se disponía de tres o más hidrogramas de crecidas para calibrar el modelo, el contenido de información de cada evento individual mostró ser menos importante e influyente en las predicciones, independientemente de las características y magnitud de los eventos.

Los datos de los hidrogramas utilizados para calibrar el modelo en el ensayo III fueron los eventos más extremos, lo que significa que son difíciles de predecir y de medir en típicas mediciones de campo. El ensayo IV puso a prueba el método de calibración del ensayo III utilizando hidrogramas de crecidas por encima de un umbral con una alta probabilidad de ocurrencia. Los hidrogramas de tales eventos demostraron ser igualmente útiles para la calibración del modelo que los de los eventos más extremos, que ocurren con menor frecuencia. Los resultados encontrados en los ensayos III y IV sugieren que se pueden necesitar menos datos de calibración si los mismos son captados con una resolución temporal alta y si se registran en forma de eventos, ya que parecen proporcionar suficiente información para definir los valores de los parámetros. Adicionalmente, una cantidad limitada de datos de crecidas demostró ser de valor para entender mejor la relación lluvia-escorrentía en cuencas de rápida respuesta y para mejorar los pronósticos de inundación en áreas con escasez de datos.

Los modelos hidrológicos vinculados a pronósticos de lluvia pueden proporcionar advertencias de crecidas en cuencas con tiempo de concentración corto. Sin embargo, errores en los pronósticos de lluvia pueden ser grandes y pueden afectar la capacidad de los modelos hidrológicos para simular las inundaciones con precisión. En el ensayo IV, se llevó a cabo un análisis de sensibilidad para evaluar los efectos de la incertidumbre en los pronósticos de lluvia en un modelo de inundación que ya estaba calibrado contra un número limitado de crecidas. Diferentes escenarios de pronósticos de lluvia se utilizaron como datos de entrada al modelo para predecir inundaciones. Estos pronósticos fueron generados en función de las observaciones de lluvia real, pero se agregaron diferentes errores de volumen y duración. Los resultados mostraron que los pronósticos de inundación fueron sensibles a ambos tipos de errores en los pronósticos de lluvia, pero los errores de volumen tuvieron el mayor impacto en los resultados del modelo. Los errores de uno parecen compensar los errores del otro, ya que se pudieron encontrar buenos resultados de modelado para errores grandes de ambos. En general, se encontró que un modelo calibrado contra un número limitado de hidrogramas de crecidas podría ser útil aun si se utiliza con pronósticos de lluvia inciertos. Los resultados del análisis de sensibilidad se pueden utilizar para mejorar los pronósticos de lluvia con un enfoque en modelos de lluvia escorrentía y, en última instancia, para obtener buenos pronósticos de inundaciones.

El acceso a datos hidro-meteorológicos es fundamental para la gestión del riesgo de inundaciones. Los métodos descritos en esta tesis muestran el valor de datos hidro-meteorológicos limitados, los cuales pueden ser útiles para predecir inundaciones. El trabajo presentado en la tesis tiene como objetivo crear conciencia sobre el valor de los datos hidro-meteorológicos limitados, espera contribuir a una mejor evaluación del riesgo de inundación en apoyo a la gestión del recurso hídrico, y última instancia, espera pueda ser de uso para limitar los daños perjudiciales por las crecidas de ríos en áreas donde la disponibilidad de datos es limitada o hace falta.

Finalmente, hay que decir que los métodos presentados en esta tesis se han desarrollado y probado en una o dos cuencas hidrográficas, y en un modelo hidrológico. La generalidad de los resultados solo se puede garantizar si los métodos se prueban con otros modelos y cuencas hidrográficas donde dominan otros procesos hidrológicos en comparación con los de Centroamérica.

References

Anctil, F., Perrin, C. & Andréassian, V. (2004) Impact of the length of observed records on the performance of ANN and of conceptual parsimonious rainfall-runoff forecasting models. *Environ. Model. Softw.* **19**(4), 357–368. doi:10.1016/S1364-8152(03)00135-X

Andréassian, V., Perrin, C. & Michel, C. (2001) Impact of imperfect rainfall knowledge on the efficiency and the parameters of watershed models. *J. Hydrol.* **250**(1–4), 206–223. doi:10.1016/S0022-1694(01)00437-1

Bastola, S. & Murphy, C. (2013) Sensitivity of the performance of a conceptual rainfall–runoff model to the temporal sampling of calibration data. *Hydrol. Res.* **44**(3), 484–493. doi:10.2166/nh.2012.061

Bergström, S. (1976) Development and application of a conceptual runoff model for Scandinavian catchments. SMHI, Report No. RHO 7. Norrköping, Sweden.

Beven, K. (2001) *Rainfall-Runoff Modelling: The Primer. Wiley, Chichester.*

Beven, K. (2009) *Environmental Modelling: An Uncertain Future?* Routledge.

Beven, K. & Binley, A. (1992) The future of distributed models: Model calibration and uncertainty prediction. *Hydrol. Process.* **6**(3), 279–298. doi:10.1002/hyp.3360060305

Blöschl, G., Reszler, C. & Komma, J. (2008) A spatially distributed flash flood forecasting model. *Environ. Model. Softw.* **23**(4), 464–478. doi:10.1016/j.envsoft.2007.06.010

Blöschl, G., Sivapalan, M., Wagener, T., Viglione, A. & Savenije, H. (2013) *Runoff Prediction in Ungauged Basins: Synthesis across Processes, Places and Scales*. Cambridge University Press. doi:10.1017/CBO9781139235761

Bormann, H., Breuer, L., Giertz, S., Huisman, J. A. & Viney, N. R. (2009) Spatially explicit versus lumped models in catchment hydrology – experiences from two case studies. In: Baveye P.C., Laba M., Mysiak J. (eds) Uncertainties in Environmental Modelling and Consequences for Policy Making. NATO Science for Peace and Security . doi:10.1007/978-90-481-2636-1_1

Brath, A., Montanari, A. & Toth, E. (2004) Analysis of the effects of different scenarios of historical data availability on the calibration of a spatially-distributed hydrological model. *J. Hydrol.* **291**(3–4), 232–253. doi:10.1016/j.jhydrol.2003.12.044

CEH. (2016) Centre for Ecology & Hydrology database. Retrieved March 7, 2016, from https://catalogue.ceh.ac.uk/documents

Cordery, I. & Cloke, P. S. (1992) Economics of Streamflow Data Collection. *Water Int.* **17**(1), 28–32. Taylor & Francis Group. doi:10.1080/02508069208686125

Dilley, M., Chen, R. S., Deichmann, U., Lerner-Lam, A. L. & Arnold, M. (2005) *Natural Disaster Hotspots: A Global Risk Analysis. Washington, DC: World Bank. © World Bank. https://openknowledge.worldbank.org/handle/10986/7376 License: CC BY 3.0 IGO.*

Ferraris, L., Rudari, R. & Siccardi, F. (2002) The Uncertainty in the Prediction of Flash Floods in the Northern Mediterranean Environment. *J. Hydrometeorol.* **3**, 714–727. doi:10.1175/1525-7541(2002)003<0714:TUITPO>2.0.CO;2

Ficchì, A., Perrin, C. & Andréassian, V. (2016) Impact of temporal resolution of inputs on hydrological model performance: An analysis based on 2400 flood events. *J. Hydrol.* **538**, 454–470. doi:10.1016/j.jhydrol.2016.04.016

Finch, J. W. & Hall, R. L. (2001) *Estimation of Open Water Evaporation*. Environment Agency, Rio House, Waterside Drive, Aztec West, Almondsbury, Bristol, BS32 4UD. Retrieved from https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/290579/sw6-043-hb-e-e.pdf

Finnerty, B. D., Smith, M. B., Seo, D.-J., Koren, V. & Moglen, G. E. (1997) Space-time scale sensitivity of the Sacramento model to radar-gage precipitation inputs. *J. Hydrol.* **203**(1–4), 21–38. doi:10.1016/S0022-1694(97)00083-8

Franchini, M. & Pacciani, M. (1991) Comparative analysis of several conceptual rainfall-runoff models. *J. Hydrol.* **122**(1–4), 161–219. doi:10.1016/0022-1694(91)90178-K

Fuentes-Andino, D. (2017) *Flood Hazard Assessment in Data- Scarce Basins Use of alternative data and modelling techniques*. Uppsala University.

Gan, T. Y., Dlamini, E. M. & Biftu, G. F. (1997) Effects of model complexity and structure, data quality, and objective functions on hydrologic modeling. *J. Hydrol.* **192**(1–4), 81–103. doi:10.1016/S0022-1694(96)03114-9

Georgakakos, K. P., Sperfslage, J. A., Tsintikidis, D. & Carpenter, T. M. (1999) Design and Tests of an Integrated Hydrometerorological Forecast System for the Operational Estimation and Forecasting of Rainfall and Streamflow in the Mountainous Panama Canal Watershed. Hydrologic Research Center, HRC Technical Report No. 2. San Diego, CA.

Girons Lopez, M. & Seibert, J. (2016) Influence of hydro-meteorological data spatial aggregation on streamflow modelling. *J. Hydrol.* **541**, 1212–1220. Elsevier B.V. doi:10.1016/j.jhydrol.2016.08.026

Häggström, M., Lindström, G., Cobos, C., Martinez, J. R., Merlos, L., Alonzo, R. D., Castillo, G., et al. (1990) Application of the HBV model for flood forecasting in six Central American rivers. SMHI Hydrology, No. 27. Norrköping, Sweden.

Jian, J., Costelloe, J., Ryu, D. & Wang, Q. J. (2017) Does a fifteen-hour shift make much difference ? – Influence of time lag between rainfall and discharge data on model calibration. *22nd Int. Congr. Model. Simul.* Hobart, Tasmania, Australia.

Jie, M. X., Chen, H., Xu, C. Y., Zeng, Q., Chen, J., Kim, J. S., Guo, S. lian, et al. (2018) Transferability of Conceptual Hydrological Models Across Temporal Resolutions: Approach and Application. *Water Resour. Manag.* **32**(4), 1367–1381. doi:10.1007/s11269-017-1874-4

Kavetski, D. & Clark, M. P. (2011) Numerical troubles in conceptual hydrology: Approximations, absurdities and impact on hypothesis testing. *Hydrol. Process.* **25**(4), 661–670. doi:10.1002/hyp.7899

Kavetski, D., Fenicia, F. & Clark, M. P. (2011) Impact of temporal data resolution on parameter inference and model identification in conceptual hydrological modeling: Insights from an experimental catchment. *Water Resour. Res.* **47**, **W05501**. doi:10.1029/2010WR009525

Kay, A. L. & Davies, H. N. (2008) Calculating potential evaporation from climate model data: A source of uncertainty for hydrological climate change impacts. *J. Hydrol.* **358**(3–4), 221–239. doi:10.1016/j.jhydrol.2008.06.005

Kobold, M. (2007) Hydrological Modelling of Floods. In: *Advances in Urban Flood Management*. Taylor & Francis.

Lindström, G., Johansson, B., Persson, M., Gardelin, M. & Bergström, S. (1997) Development and test of the distributed HBV-96 hydrological model. *J. Hydrol.* **201**(1–4), 272–288. doi:10.1016/S0022-1694(97)00041-3

Littlewood, I. G. (2007) Rainfall-Streamflow for Ungauged Basins: Uncertainty Due to Modelling Time-Step, in: 11th Conference of the Euromediterranean Network of Experimental and Representative Basins (ERB), Luxembourg, 20–23 September 2006, 149–155.

Littlewood, I. G. & Croke, B. F. W. (2008) Data time-step dependency of conceptual rainfall—streamflow model parameters: an empirical study with implications for regionalisation. *Hydrol. Sci. J.* **53**(4), 685–695. doi:10.1623/hysj.53.4.685

Littlewood, I. G. & Croke, B. F. W. (2013) Effects of data time-step on the accuracy of calibrated rainfall–streamflow model parameters: practical aspects of uncertainty reduction. *Hydrol. Res.* **44**(3), 430–440. doi:10.2166/nh.2012.099

Lott, N., McCown, S., Graumann, A., Ross, T. & Lackey, M. (1999) Hurricane Mitch 1999; NOAA's National Climatic Data Center, Asheville, NC.

Luo, T., Maddocks, A., Iceland, C., Ward, P. & Winsemius, H. (2015) World's 15 Countries with the Most People Exposed to River Floods. Retrieved August 1, 2016, from http://www.wri.org/blog/2015/03/world's-15-countries-most-people-exposed-river-floods

Marengo, J. A., Chou, S. C., Torres, R. R., Giarolla, A., Alves, L. M. & Lyra, A. (2014) Climate change in Central and South America: Recent trends, future projections, and impacts on regional agriculture. CCAFS Working Paper no. 73. Copenhagen, Denmark: CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS).

Maskey, S. (2004) *Modelling Uncertainty in Flood Forecasting Systems*. Delf University of Technology.

McGlynn, B. L., Blöschl, G., Borga, M., Bormann, H., Hurkmans, R., Komma, J., Nandagiri, L., et al. (2013) A data acquisition framework for runoff prediction in ungauged basins. In: *Runoff Prediction in Ungauged Basins: Synthesis across Processes, Places and Scales* (G. Blöschl, M. Sivapalan, T. Wagener, A. Viglione & H. Savenije, eds.), 29–52. Press, Cambridge University. doi:10.1017/CBO9781139235761.006

McIntyre, N. R. & Wheater, H. S. (2004) Calibration of an in-river phosphorus model: Prior evaluation of data needs and model uncertainty. *J. Hydrol.* **290**(1–2), 100–116. doi:10.1016/j.jhydrol.2003.12.003

Melsen, L. & Teuling, A. (2014) Catchments as simple dynamical systems: A case study on methods and data requirements for parameter identification. *Water Resour. Res.* **50**(7), 5577–5596. doi:10.1002/2013WR014720

Michel, C., Perrin, C. & Andreassian, V. (2003) The exponential store: a correct formulation for rainfall—runoff modelling. *Hydrol. Sci. J.* **48:1**, 109–124. doi:10.1623/hysj.48.1.109.43484

Mucke, P., Radtke, K., Luther, S., Kirch, L., Prütz, R. & Schrader, C. (2017) World Risk Report: Analysis and prospects 2017.

Nalbantis, I. (1995) Use of multiple-time-step-information in rain-fall runoff modelling. *J. Hydrol.* **165**(1–4), 135–159. doi:10.1016/0022-1694(94)02567-U

Natural Environment Research Council (NERC). (2003) *Hydrometric Register and Statistics 1996-2000*. Centre for Ecology and Hydrology, Wallingford, UK.

Ostrowski, M., Bach, M., Desimone, S. V & Gamerith, V. (2010) *Analysis of the time-step dependency of parameters in conceptual hydrological models*. Technische Universität Darmstadt, Darmstadt, Germany, 31 pp.

Parajka, J., Andréassian, V., Archfield, S. A., Bárdossy, A., Blöschl, G., Chiew, F., Duan, Q., et al. (2013) Prediction of runoff hydrographs in ungauged basins. In: *Runoff Prediction in Ungauged Basins: Synthesis across Processes, Places and Scales* (G. Blöschl, M. Sivapalan, T. Wagener, A. Viglione, H. Savenije, C. J. Parajka & V. Andréassian, eds.), 227–269. Cambridge University Press. doi:10.1017/CBO9781139235761.013

Quesada-Montano, B. (2017) *Hydro-Climatic Variability and Change in Central America: Supporting Risk Reduction Through Improved Analyses and Data*. Uppsala University.

Reynolds, J. E. (2012) *Usability of Standard Monitored Rainfall-Runoff Data in Panama , Juan Diaz River Basin, M.S. thesis* (No. ISSN 1650-6553 Nr 242). Uppsala University, Uppsala, Sweden, 62 pp.

Romanowicz, R. J., Young, P. C. & Beven, K. J. (2006) Data assimilation and adaptive forecasting of water levels in the river Severn catchment, United Kingdom. *Water Resour. Res.* **42**(6), 1–12. doi:10.1029/2005WR004373

Ropelewski, C. F. & Halpert, M. S. (1987) Global and Regional Scale Precipitation Patterns Associated with the El Niño/Southern Oscillation. *Mon. Weather Rev.* **115**, 1606–1626. doi:10.1175/1520-0493(1987)115<1606:GARSPP>2.0.CO;2

Rosbjerg, D., Blöschl, G., Burn, D. H., Castellarin, A., Croke, B., Baldassarre, G. Di, Iacobellis, V., et al. (2013) Prediction of floods in ungauged basins. In: *Runoff Prediction in Ungauged Basins: Synthesis across Processes, Places and Scales* (G. Blöschl, M. Sivapalan, T. Wagener, A. Viglione & H. Savenije, eds.), 189–226. Cambridge University Press. doi:10.1017/CBO9781139235761.012

Santos, L., Thirel, G. & Perrin, C. (2018) Continuous state-space representation of a bucket-type rainfall-runoff model: a case study with the GR4 model using state-space GR4 (version 1.0). *Geosci. Model Dev.* **11**(4), 1591–1605. doi:10.5194/gmd-11-1591-2018

Schanze, J., Zeman, E. & Marsalek, J. (2006) *Flood Risk Management: Hazards, Vulnerability and Mitigation Measures*. NATO Science Series IV. Earth and Environmental Sciences: Vol. 67. Springer Netherlands.

Seibert, J. (1999) Regionalisation of parameters for a conceptual rainfall-runoff model. *Agric. For. Meteorol.* **98–99**, 279–293. doi:10.1016/S0168-1923(99)00105-7

Seibert, J. & Beven, K. (2009) Gauging the ungauged basin: how many discharge measurements are needed? *Hydrol. Earth Syst. Sci.* **13**(6), 883–892. doi:10.5194/hess-13-883-2009

Seibert, J. & McDonnell, J. J. (2013) Gauging the Ungauged Basin: The Relative Value of Soft and Hard Data. *J. Hydrol. Eng.* **20**(1). doi:10.1061/%28ASCE%29HE.1943-5584.0000861

Seibert, J., Vis, M., Lewis, E. & Meerveld, I. van. (2018) Upper and lower benchmarks in hydrological modeling. *Hydrol. Process.* **32**(8), 1120–1125. doi:10.1002/hyp.11476

Sikorska, A. E., Viviroli, D. & Seibert, J. (2015) Flood-type classification in mountainous catchments using crisp and fuzzy decision trees. *Water Resour. Res.* **51**(10), 7959–7976. doi:10.1002/2015WR017326

Sorooshian, S., Gupta, V. K. & Fulton, J. L. (1983) Evaluation of Maximum Likelihood Parameter Estimation Techniques for and Length on Model Credibility. *Water Resour. Res.* **19**(1), 251–259. doi:10.1029/WR019i001p00251

Stokstad, E. (1999) Scarcity of Rain, Stream Gages Threatens Forecasts. *Science.* **285**(5431), 1199–1200. doi:10.1126/science.285.5431.1199

Tada, T. & Beven, K. J. (2012) Hydrological model calibration using a short period of observations. *Hydrol. Process.* **26**(6), 883–892. doi:10.1002/hyp.8302

UNESCO. (2012) Inventario y caracterización de los Sistemas de Alerta Temprana en América Central.

USGS. (2016) U.S. Geological Survey. Retrieved March 7, 2016, from http://hydrosheds.cr.usgs.gov/datadownload.php?reqdata=3demg

Vincent, L. A., Milewska, E. J., Hopkinson, R. & Malone, L. (2009) Bias in minimum temperature introduced by a redefinition of the climatological day at the canadian synoptic stations. *J. Appl. Meteorol. Climatol.* **48**(10), 2160–2168. doi:10.1175/2009JAMC2191.1

Wang, Y., He, B. & Takase, K. (2009) Effects of temporal resolution on hydrological model parameters and its impact on prediction of river discharge / Effets de la résolution temporelle sur les paramètres d'un modèle hydrologique et impact sur la prévision de l'écoulement en rivière. *Hydrol. Sci. J.* **54:5**, 886–898. doi:10.1623/hysj.54.5.886

Westerberg, I. K., Gong, L., Beven, K. J., Seibert, J., Semedo, A., Xu, C.-Y. & Halldin, S. (2014) Regional water balance modelling using flow-duration curves with observational uncertainties. *Hydrol. Earth Syst. Sci* **18**(8), 2993–3013. doi:10.5194/hess-18-2993-2014

Westerberg, I., Walther, A., Guerrero, J.-L., Coello, Z., Halldin, S., Xu, C.-Y., Chen, D., et al. (2010) Precipitation data in a mountainous catchment in Honduras: quality assessment and spatiotemporal characteristics. *Theor. Appl. Climatol.* **101**(3–4), 381–396. doi:10.1007/s00704-009-0222-x

WMO. (2011) Manual on Flood Forecasting and Warning (WMO-No. 1072).

Xu, C. (2002) *Hydrologic Models*. Uppsala, Sweden: Uppsala University, Department of Earth Sciences.

Xu, H., Xu, C. Y., Chen, H., Zhang, Z. & Li, L. (2013) Assessing the influence of rain gauge density and distribution on hydrological model performance in a humid region of China. *J. Hydrol.* **505**, 1–12. doi:10.1016/j.jhydrol.2013.09.004

Yapo, P. O., Gupta, H. V. & Sorooshian, S. (1996) Automatic calibration of conceptual rainfall-runoff models: sensitivity to calibration data. *J. Hydrol.* **181**(1–4), 23–48. doi:10.1016/0022-1694(95)02918-4

Acta Universitatis Upsaliensis

Digital Comprehensive Summaries of Uppsala Dissertations from the Faculty of Science and Technology 1753

Editor: The Dean of the Faculty of Science and Technology

A doctoral dissertation from the Faculty of Science and Technology, Uppsala University, is usually a summary of a number of papers. A few copies of the complete dissertation are kept at major Swedish research libraries, while the summary alone is distributed internationally through the series Digital Comprehensive Summaries of Uppsala Dissertations from the Faculty of Science and Technology. (Prior to January, 2005, the series was published under the title "Comprehensive Summaries of Uppsala Dissertations from the Faculty of Science and Technology".)

ACTA
UNIVERSITATIS
UPSALIENSIS
UPPSALA
2019

Distribution: publications.uu.se
urn:nbn:se:uu:diva-368532