UPPSALA
UNIVERSITET

Digital Comprehensive Summaries of Uppsala Dissertations from the Faculty of Science and Technology 1832

Design flood estimation under uncertainty

KENECHUKWU OKOLI

ACTA
UNIVERSITATIS
UPSALIENSIS
UPPSALA
2019

ISSN 1651-6214
ISBN 978-91-513-0706-0
urn:nbn:se:uu:diva-390362

Dissertation presented at Uppsala University to be publicly examined in Hambergsalen Geocentrum, Villavägen 16, Uppsala, Friday, 27 September 2019 at 17:44 for the degree of Doctor of Philosophy. The examination will be conducted in English. Faculty examiner: Prof. Dr. rer.nat. Dr.-Ing. András Bárdossy (University of Stuttgart, Germany).

Abstract

Okoli, K. 2019. Design flood estimation under uncertainty. *Digital Comprehensive Summaries of Uppsala Dissertations from the Faculty of Science and Technology* 1832. 47 pp. Uppsala: Acta Universitatis Upsaliensis. ISBN 978-91-513-0706-0.

A common task in hydrology is the estimation of the design flood, i.e. a value of river discharge corresponding to a given exceedance probability that is often expressed as a return period in years. Flood risk assessment, floodplain mapping and the design of hydraulic structures are a few examples of applications where estimates of design floods are required. Common approaches for estimating a design flood are based on: (i) hydrological methods such as continuous simulations with rainfall–runoff models, or (ii) statistical methods, such as the fitting of a probability distribution function to a record of annual maximum values. In this thesis, these alternative approaches are compared in view of the various sources of uncertainties affecting the estimation of the design flood. Since design floods are typically not known a priori, a series of virtual experiments was developed and implemented for both estimation methods, hence the magnitudes and frequencies of the design floods are known ab initio, and the quality of estimates (i.e., in terms of their accuracy and precision) were analysed. These virtual experiments are defined as ‘numerical experiments with a model considered as the truth and best understanding of the modelled processes’. This thesis looked at the influence of method of estimation, model structure uncertainty, errors in the flow data, and sampling on design flood estimation. The results show that design floods estimated by using a simple rainfall-runoff model have small uncertainties (i.e., variance of the errors) even for high return periods compared to statistical methods. Statistical methods performed better than the simple rainfall-runoff model in terms of median errors for high return periods, but their uncertainty (i.e. variance of the error) is larger. The thesis concludes that given the sources of uncertainty of statistical and hydrological methods, they both should be applied as complementary.

Keywords: Design flood, uncertainty, rainfall-runoff, frequency analysis.

Kenechukwu Okoli, Department of Earth Sciences, Villav. 16, Uppsala University, SE-75236 Uppsala, Sweden.

ISSN 1651-6214
ISBN 978-91-513-0706-0
urn:nbn:se:uu:diva-390362 (http://urn.kb.se/resolve?urn=urn:nbn:se:uu:diva-390362)

Akademisk avhandling som för avläggande av teknologie doctorsexamen i hydrologi vid Uppsala universitet kommer att offentligen försvaras i Hambergsalen, Villavägen 16, Uppsala, fredagen 27 september 2019, klockan 10:00. Fakultetsopponent: Prof. Dr. rer.nat. Dr.-Ing. András Bárdossy (Universitet Stuttgart, Germany). Disputationen sker på engelska.

Referat

Okoli, K. 2019. Uppskattning av dimensionerande flöden med osäkerheter. *Digital Comprehensive Summaries of Uppsala Dissertations from the Faculty of Science and Technology*. 47 sidor. Uppsala. ISBN 978-91-513-0706-0

Att bestämma dimensionerande flöden, d.v.s. sannolikheten för att vattenföringen i ett vattendrag överskrider ett givet värde, är ett allmänt hydrologiskt problem som exempelvis används för att utvärdera översvämningsrisker i vattendrag samt för att dimensionera hydrauliska konstruktioner. Vanliga tillvägagångsätt för att bestämma dimensionerande flöden är baserade på: (i) hydrologiska metoder (t.ex. avrinningsmodellering), eller (ii) statistiska metoder (t.ex. anpassning av en sannolikhetsfördelning till en tidsserie med årliga vattenföringstoppar). I denna avhandling så jämförs dessa två tillvägagångssätt då olika osäkerhetskällor för dimensionerande flöden tillgodoses; valet av tillvägagångsätt, osäkerhet i modellens uppbyggnad, osäkerheter i vattenföringsmätningar, samt mätfrekvens av dimensionerande flöden, begrundades i denna avhandling. Sannolikhetsfördelningen av vattenföringen i ett hypotetisk vattendrag antogs vara känt sedan tidigare; en uppsättning av virtuella experiment ('numeriska experiment där modellen antas vara sann och beskriva den modellerade processen korrekt') utvecklades och tillämpades för båda tillvägagångssätten som utvärderades utifrån hur väl de uppskattade den sedan tidigare kända sannolikhetsfördelningen av vattenföringen. Resultaten visar att användningen av enklare avrinningsmodeller för att bestämma dimensionerande flöden har en lägre osäkerhet än då statistiska metoder används, även för längre återkomstperioder. Båda tillvägagångsätten bör dock användas som komplement till varandra för att bestämma dimensionerande flöden, givet osäkerheten i båda.

Nyckelord: dimensionerande flöden, osäkerheter, avrinningsmodellering, frekvens analys.

Kenechukwu Okoli, Institutionen för geovetenskaper, LUVAL, Villavägen 16, Uppsala universitet, 752 36 Uppsala, Sverige.

ISSN 1651-6214
ISBN 978-91-513-0706-0

urn:nbn:se:uu:diva-390362 (http://urn.kb.se/resolve?urn=urn:nbn:se:uu:diva-390362)

Dedicated to my family, friends and mentors.

List of Papers

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

I **Okoli, K.**, Breinl, K., Brandimarte, L., Botto, A., Volpi, E., Di Baldassarre, G. (2018) Model averaging versus model selection: estimating design floods with uncertain river flow data. *Hydrological Science Journal*, 63(13-14), 1913-1926.

II **Okoli, K.**, Breinl, K., Mazzoleni, M., Di Baldassarre, G. (2019) Design Flood Estimation: Exploring the Potentials and Limitations of Two Alternative Approaches. *Water*, 11(4), 729.

III **Okoli, K.**, Mazzoleni, M., Breinl, K., Di Baldassarre, G. (2019) A systematic comparison of statistical and hydrological methods for design flood estimation. *Hydrology Research,* accepted after minor revision.

IV **Okoli, K.**, Mazzoleni, M., Breinl, K., Di Baldassarre, G. (2019) Evaluation of design flood estimates – a case study for Rome. *Manuscript*.

Contents

1. Introduction

1.1 Background

Flooding can often result in undesired consequences such as economic losses, environmental degradation, displacement of people and, more importantly, loss of lives. A recent example is the flooding that hit Zimbabwe, Malawi and Mozambique earlier this year (2019) with many cities and villages flooded. In addition, the recent trend in increased flood magnitudes and occurrence frequency has been generally attributed to climatic changes. A reliable estimate of extreme floods is important for hydrology as a scientific enterprise, and also informs decision-makers about flood risk assessment and management. As a result, methods of flood estimation need to be developed, tested and their reliability reported for the benefit of all stakeholders.

Methods for flood estimation are used for the design of hydraulic structures used for the conveyance of flood flows (culverts, diversion channels, spillways) or for structural protection from flooding (levees and detention basins). The estimated flows are commonly referred to as “Design Floods” among practitioners who make use of such information to carry out various tasks related to water management. Two methods for flood estimation have been suggested in the field of hydrology:

1. Statistical methods – generally referred to as “Flood Frequency Analysis”, which requires the fitting of a probability distribution function to a record of annual maximum flows. Usually, the frequency of occurrence (or return period) is specified and the corresponding magnitude of flood is calculated by inverting the fitted probability distribution function (Moran, 1957; Klemeš, 2000). The origin of this method can be traced back to papers published in engineering journals in the beginning of the early 20th century (Fuller, 1914; Hazen, 1914). With Fréchet (1927) and Fisher and Tippet (1928) providing the theoretical foundations of extreme value statistics, this method has remained relevant to both real applications and hydrology research (Gaume, 2018; Kobierski et al. 2018).

2. Hydrological methods – refers to the estimation of design floods based on mathematical models that describe the physical processes that influence the transformation of rainfall to runoff. For instance,

the influence of threshold effects (e.g. catchment storage) on flood frequency curves can only be explained using physically based hydrological models (Rogger et al., 2012). The models used are generally referred to as rainfall-runoff models (RR). Some examples of RR models are the rational formula by Mulvaney (1874), the linear reservoir (Buytaert, 2004), HBV (Bergström, 1992; Seibert 1997) and TOPMODEL (Beven and Kirkby, 1979; Beven, 1986, 1987), just to mention a few. RR models can be used in two different simulation modes for the estimation of a design flood. The first one is the "event-based simulation" (EBS) that requires the selection of a design rainfall from an intensity duration frequency (IDF) curve of rainfall with a given duration and assumed profile and uses it as input into the RR model to derive the flood hydrograph (Rogger et al., 2012). However, event-based approaches are limited in the fact that they do not account for the role of antecedent moisture content in runoff generation (which can be important for flood assessment). The second simulation mode is known as "continuous simulation" (CS) and can be based on the coupling of a stochastic weather model (Bárdossy et al., 1992) with a RR model. The latter approach treats the discharge as a single term without prior separation into overland flow and baseflow. The problem of antecedent moisture content of the catchment is addressed implicitly as part of the modelling procedure (Calver and Lamb, 1995). Example applications of CS for flood estimation hydrology can be found in studies by Blazkova and Beven (1997), Cameron et al (1999) and Pathiraja et al (2012).

The two design flood methods described above require the specification of potential models – statistical or hydrological. These models are now considered as candidates to be used for the quantification of hydrological risk, in this case, to estimate the size of an extreme river discharge with a selected frequency of occurrence. The two methods are affected by several sources of uncertainties such as imperfect model structures (Bodo et al., 1976; Beven, 2012), erroneous observation in hydrological and meteorological variables (Di Baldassarre and Montanari, 2009; Westerberg and McMillan, 2015), imperfect parameter estimates due to records that are disinformative or with recording gaps present in them (Bárdossy, 2007; Bárdossy and Singh, 2008; Beven and Westerberg, 2011). With regards to hydrological methods, uncertainties might arise also due to imperfect geometric description of control volume or inexact initial states and boundary conditions (Beven, 2012; Koutsoyiannis, 2010). While for statistical methods, uncertainties might arise from the choice of sample (annual maximum flows versus peaks-over-threshold), and method of estimating parameters of the selected distribution (method of moments, L-moments and maximum likelihood).

Another common problem in design flood estimation is that different model structures will lead to different estimates of the design flood. This point is demonstrated using an example based on statistical methods as shown in Figure 1. Supposing the 100-year flood is the event of interest, Figure 1 shows that the design flood estimate varies among the fitted distribution functions. Selecting one of these estimates (and ignoring the rest), in any real application, might lead to flood management solutions that are not robust against uncertainties that arise when a wrong distribution function is used for estimation purposes.

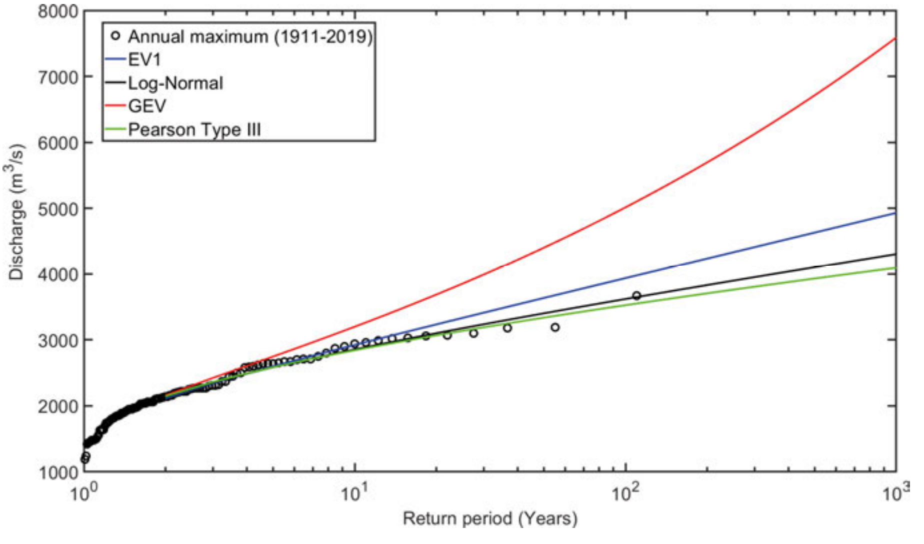


Figure 1. A plot showing the fit of different distribution functions to a record of annual maximum flows at Kukkolankoski Övre, a gauging station located in the northern part of Sweden.

The hydrological literature has quite a number of studies comparing statistical and hydrological methods for design flood estimation. Rogger et al. (2012) compared statistical, EBS and CS approaches in ten small Austrian catchments based on observation data at sub-hourly resolution. Grimaldi et al. (2012) and Grimaldi et al. (2013) compared CS modelling with EBS approaches in small ungauged watersheds in Italy using spatially uniform rainfall at sub-hourly resolution. Winter et al. (2019) compared CS modelling, EBS and statistical approaches in small Alpine catchments in Austria using sub-daily time series. The conclusion from these studies is that EBS methods lead to an underestimation of the design flood while statistical and CS methods lead to comparable results. Also, since all these studies are based on real data, and design floods are not known in advance, it is difficult to conduct a systematic assessment of the two methods of estimation.

Virtual experiments - in other words, synthetic experiments - were used in this thesis to circumvent the problem of not knowing in advance the true value of the design flood, and also for benchmarking results. They are defined as 'numerical experiments with a model considered as the truth and best understanding of the modelled processes'. These synthetic experiments were developed and implemented for both estimation methods, hence the magnitudes and frequencies of the design floods are known ab initio, and the quality of estimates (i.e., in terms of their accuracy and precision) were analysed.

1.2 Aim of thesis

This work aims to investigate the influence of different sources of uncertainties on the accuracy and precision of design flood estimates.

In specific details, the aims of the thesis were divided into three parts:

- i Evaluating the consequences of errors in the flow data, length of sample and bias as a result of the choice of distribution function (**Papers I, II, III, and IV**).
- ii Develop a methodology to compare statistical and hydrological methods of design flood estimation (**Paper III**).
- iii Develop a methodology to compare flood frequency analysis based on records of annual flood levels versus records of annual maximum flows (**Paper II**).

2. Theoretical Background

"In relation to this topic, my criticism was directed to those who do not see this simple fact and confuse the substance with the form, and try to deduce hydrological truths not from the features of water movement in nature but from the features of black boxes, transfer functions, sampling properties of random numbers, proofs of mathematical theorems, etc." - Vit Klemeš

"...asymptotic arguments is used to generate extreme value models. It is easy to be cynical about this strategy, arguing that extrapolation of models to unseen levels requires a leap of faith, even if the models have an asymptotic rationale. There is no simple defense against this criticism, except to say that applications demand extrapolation, and that it is better to use techniques that have a rationale of some sort. " - Stuart Coles

2.1 Basic concepts of flood analysis

Design flood estimation is concerned with the quantification of an extreme river flow whose frequency of occurrence is expressed in terms of return period *T*. The design flood is conceived on an annual basis as the *T*-year flood and is defined as the average time (in years) that it takes for a flood of a given magnitude to be equaled or exceeded. Consider a gauging site where a long, continuous record of river flows *Q* is available. There will be some probability

$$p = Pr(Q > Q^*) \tag{1}$$

of observing flows exceeding Q^*. This exceedance probability *p* has an inverse relation with *T*, and is expressed mathematically as,

$$T = \frac{1}{P} \tag{2}$$

Equation 2 suggests that the higher the return period of a flood the lower the probability of exceedance, and vice versa. It should be mentioned that the notion of return period has been criticized, as it may give the impression (to non-experts) that the stochastic process being modelled is periodic (Volpi, 2018). Some researchers (e.g. Read and Vogel, 2015) have called for its replacement and recommended the use of reliability for the design of flood control works. Reliability is defined as the probability that a system will remain in satisfactory state (Hashimoto et al., 1982; Salas and Obeysekera, 2014) during its lifetime,

Two types of sampling strategy can be used for flood frequency or design flood estimation. The first one is the block maxima, otherwise known as the annual maximum series. In this case, the maximum flow in each hydrological year is extracted from a continuous hydrograph to build a sample of annual maximum flows. The second one is based on flood peaks over a threshold, where the threshold is set to include at least three peaks per year (Cunnane, 1979). The peaks-over-threshold (POT) or partial duration series provides a larger sample for flood analysis. However, these selected peak flows may be still part of one or more dependent storm events. Various empirical procedures are used to ensure independence between events by specifying a time separation between successive flow peaks (Cunnane, 1979).

The relationship between Q and T is referred to as the flood frequency curve. The leap from frequency to probability of exceeding Q^* can only be made if there is a long continuous record of Q, and the catchment and climate conditions are considered stationary. These conditions are rarely satisfied in any practical application because we are often interested in peak flows whose return periods are far beyond the maximum on record. Also, the climate and many catchments are heavily influenced by humans, through emission of greenhouse gases (GHG), deforestation and urbanization, just to mention a few.

2.2 Statistical method

The statistical method for design flood estimation requires the fitting of a probability distribution function to available records of peak flows. The most used families of distributions popular in flood frequency analysis, with well-established theoretical support, are the three extreme value (EV) distributions (Gumbel or EV I, Frechet or EV II, and Weibull or EV III) or the synthetic form of these three distributions called general extreme value (GEV) distribution, the three parameter gamma (also called Pearson III), log-normal and log-Pearson III (the logarithm of flows in the record has a normal or Pearson III distribution). The use of any of these distribution functions is the same as providing a rationale (in the spirit of the quote by Staurt Coles) suggesting that the variability observed in the flow record can be adequately described by the selected distribution.

The sequence of annual maximum flows $x_i = (x_1, x_2, \ldots, x_n)$ is assumed to be a random sample drawn from a population with a probability density function (pdf) $f\,(x|\theta)$. Let the notation $f\,(x|\theta)$ denote the probability density of a random variable x conditioned on particular values of parameter set θ. When the analytical forms of $f\,(x|\theta)$ and θ are known, the design flood (or T-year flood) is that of magnitude $x(T)$ where

$$1 - \int_{x^*}^{x(T)} f(x|\theta)\, dx = {}^{1}/_{T} \tag{3}$$

and x^* denotes the lower bound of the population. This lower bound is the case of zero discharge. In any real application, the analytical form of $f\,(x|\theta)$ is not known a priori. A family of probability distribution functions are to be specified as potential candidates and their parameters must be estimated using the available data.

Implicit in the statistical method for design flood estimation is the assumption that the flow data are samples drawn from a homogenous population, and are stationary. However, process understanding of hydrological systems have shown that floods are a result of rainfall, snowmelt, or a combination of both (Tarasova et al., 2019). Thus, such physical understanding motivated the development of mixed distributions, for example, the Two Component Extreme Value (TCEV) distribution by Rossi et al. (1984). Non-stationary methods for frequency analysis of a hydrological variable of interest is now an active area of research in hydrology (Strupczewski et al. 2001; Cheng and AghaKouchak, 2014; Salas et al. 2018), especially with observed changes happening in almost every aspect of the hydrological system.

The flow data used in inferring the parameters of the selected probability distribution function are derived using an uncertain rating curve. Some studies have shown that errors in observed data have an impact on design flood estimates (Di Baldassarre et al., 2012). Limited samples and choice of inference method (maximum likelihood, method of moments, L-moments), including the choice of distribution function, are reported to impact the accuracy of estimated design floods (Di Baldassarre et al., 2009).

The concepts described so far are applied to at-site flood frequency analysis, i.e. design flood estimates determined for a giving gauging location. However, the design (or operation) of hydraulic structures often require the estimation at ungauged or poorly gauged locations. The estimation of design variable at ungauged locations is addressed by using regionalization techniques (Blöschl, G. et al. 2013).

Statistical methods of design flood estimation has faced some criticism as a result of its near lack in the use of knowledge from flood processes (Klemeš, 2000).

2.3 Hydrological method

Design flood estimation based on hydrological methods is a step forward towards providing a methodology that will provide a treatment of causative factors with a conceptual model closely linked to physical processes (Lamb, 2005). Hydrological models that are used for estimation purposes are commonly referred to as RR models (Beven, 2012). The hydrological literature is replete with different kinds of models which makes it difficult to make a systematic review. However, a general view will be presented in this section with a focus on CS.

Continuous streamflow simulations for design flood estimation refer to the assessment of losses from rainfall and the generation of stream flow by simulating the wetting and drying of a catchment at daily, hourly and occasionally sub-hourly time steps (Boughton and Droop, 2003). CS represents a step forward from EBS methods of estimation and allows the extraction of different kinds of information such as, flood peaks, flood volumes and the simulation of a continuous discharge hydrograph (Lamb, 2005). Supposing the distribution function of flows is denoted as H_Y, a rainfall-runoff model that will be used for CS can be described mathematically as follows:

$$H_Y\,(y) = H_Y\,(y|M[\Theta_M, x, \mathbf{B}_M(t)]) \tag{4}$$

where flow events y are outputs of a RR model, M, which contains a vector of parameters, Θ_M, x as state variables, and a vector of time-varying boundary conditions, $\mathbf{B}_M(t)$. The inputs to the RR model may be derived from different sources as weather records e.g. observed time series of precipitation and temperature. In some cases (e.g. this thesis), $\mathbf{B}_M$ can be a long time series of synthetic weather data generated using a weather model,

$$\mathbf{B}_M = W\,(t, \Theta_W) \tag{5}$$

where Θ_W is a vector of model parameters and t is time. The weather model W serves as a key stochastic component, allowing the hydrological system to be modelled deterministically through M, although for uncertainty analysis, parameters of the weather model and RR model may be sampled from distributions as demonstrated in the study by Lamb (2016). Due to the non-linearity of both weather and RR models, it is expected their parameters will interact in complex ways and result in uncertainty in the flood frequency curve and design flood estimate.

In principle, M in Equation 4 could be any RR model. Lamb (2005) and Beven (2012) provide reviews of models applied in CS studies. Numerous studies have exploited the use of CS applications in design flood estimation (Blazkova and Beven, 1997; Cameron, 1999; Lamb et al., 2016; Breinl, 2016).

3. Materials and method

This section describes the methods that were used or developed in the four papers attached to this thesis. A series of comparative analyses were made between model selection (MS) and model averaging (MA) in order to understand their influence on design flood estimations. MS can be defined as the selection of a single best distribution function from a range of distributions considered for design flood estimation. While MA takes the design flood estimates from a range of distributions and combines them in order to obtain a skillful and reliable estimate (Höge et al., 2019). Two methods of MA were implemented: (1) weighted model averaging (WMA), which requires assigning differential weights to the range of distribution functions considered with the best fitted distribution having the highest weight. (2) model mean (MM), which is based on equal weighting, i.e. arithmetic mean of all design flood estimates. MS and MA were implemented within an information theoretic framework, specifically, the Akaike Information Criteria (Akaike, 1973).

In this thesis, Papers I, II and III are based on numerical experiments that exploited the use of synthetic flow data in analyzing different sources of uncertainties that affect design floods and levels. The main reason for the experimental design is that it provides an opportunity to systematically evaluate different techniques as one model (statistical or hydrological) is assumed to be the "true model", with parameters and design floods determined in advance. This true model and its design flood estimates are used to compare the estimates from statistical techniques, distribution functions and hydrological models. The true model is also used for generating synthetic data that are used in further analyses. The methods implemented will be described conceptually in the following sections, to allow them to be replicable on any location of study. The results from the application of each method in the study area are discussed in Section 4.

3.1 Model selection *versus* model averaging (Paper I)

The aim of this study was to investigate the influence of MS, WMA (denoted as MA in **Paper 1)** and MM on design flood estimates. While MS, WMA, MM are focused on analyzing the model choice uncertainty, the estimation problem was further analyzed by considering different observation errors in the flow data and varying sample lengths. The 100-year flood was used as the event of interest.

The first step in this study was to select the five-parameter wakeby as the true distribution. The parameters of the wakeby distribution where fixed according to recommendations by Landwehr et al. (1980). Following the recommendations of Landwehr et al. (1980), five different parameterizations of the wakeby distribution were used in five different experiments as true distributions. The distinguishing factor amongst these true distributions is that they vary in skewness. The wakeby quantile function is described as follows:

$$x = a[1-(1-F)^{b}] - c[1-(1-F)^{-d}] + m \tag{6}$$

where alphabets *a*, *b*, *c*, *d* and *m* represent the distribution parameters, x is the design flood for a given return period T, and F is the non-exceedance probability. Each wakeby distribution (with its fixed parameters), is used in calculating a true design flood and to generate synthetic flow data of a given length. Observation errors were introduced by using the error model for uncorrelated observation errors by Kuczera (1992).

Four commonly used probability distribution functions were considered as alternative candidates for design flood estimation. The parameters of the distributions were inferred using the method of maximum likelihood.

Table 1. Probability distribution functions used in this study

Distribution function	Parameters	PDF or CDF
Gumbel or EV1	(θ_1, θ_2)	$F(x,\theta) = exp[-exp(-(x-\theta_1)/\theta_2]$
Generelised Extreme Value (GEV)	$(\theta_1, \theta_2, \theta_3)$	$F(x,\theta) = exp\left[-(1-(\theta_3-(x-\theta_1)/{\theta_2}^{1/\theta_3}\right]$
Peason Type III (P3)	$(\theta_1, \theta_2, \theta_3)$	$f(x,\theta) = [1/(\lvert\theta_2\rvert\Gamma(\theta_3+1)](x-\theta_1)/{\theta_2}^{\theta_3-1} exp(-[(x-\theta_1)]/\theta_2)$
Log Normal	(θ_1, θ_2)	$f(x,\theta) = 1/\sqrt[x]{2\Pi\theta_2}\, exp\left[-1/2\,(logx-\theta_1)/{\theta_1}^2\right]$

The AIC index (I) is used for selecting the best distribution among a range of distribution functions considered and is expressed as:

$$I = -2L(\hat{\theta}) + 2K \tag{7}$$

where K is the number of parameters of the distribution function, $L(\hat{\theta})$ is the numerical value for the log-likelihood at its maximum point for the selected model and $\hat{\theta}$ is the maximum likelihood estimator of model parameters (Burnham and Anderson, 2002). Equation 7 is used in calculating the AIC for all distribution functions. The distribution with the minimum I becomes the best to use for estimation, thus MS. Akaike weights w were computed for each distribution function and used to obtain a WMA estimate of the design flood. w is expressed as:

$$w_i = exp(-1/2\Delta_i)/\sum_{r=1}^{R} exp(-1/2\Delta_r) \quad i = 1,2, \dots R \tag{8}$$

where R is the number of models considered and Δ_i is called the 'Akaike difference'. It (Akaike difference) represents the discrepancy between the best model with the minimum AIC and the i^{th} model.

For each of the generated flow samples, MS, WMA and MM are implemented with the estimates compared with the true design flood. The procedure is repeated 1000 times and the results presented in terms of relative errors.

3.2 Common *versus* alternative approaches of design flood level estimation (Paper II)

This study aimed at exploring the potentials of estimating design flood levels based on frequency analysis of annual maximum levels, and compare it with the most common approach i.e. frequency analysis of annual maximum flows. The rationale is that the latter approach involves a cascade of three models that are potential sources of uncertainties. These models are: (1) rating curves to convert water levels to discharge. (2) distribution functions to extrapolate flow record and estimate design peak flow (3) hydraulic models that converts the design peak flow back to design flood level. Frequency analysis on water levels is common place when it comes to quantifying the risk associated with coastal flooding (Xu et al. 2018; Chen et al. 2014; Razmi et al. 2017), but there are only a few studies for river flooding applications (Dyhouse, 1985).

In this study, GEV was selected as the parent distribution and used to generate synthetic flow data. The GEV parameters were estimated based on maximum likelihood, and a 90 year record of annual maximum flows (1920 -2009) at the gauge station in Pontelagoscuro located in the Po River in Italy. The parameterized GEV is used to estimate the design peak flow with a return period of 100-years. The design peak flow is used as input into a calibrated HEC-RAS model by Brandimarte and Di Baldassarre (2012) to derive the corresponding design flood level. The two values (design peak flow and level) are considered as through and used as benchmarks for the sake of comparing the two approaches. The HEC-RAS model was developed for a 98km reach of the Po River between Cremona and Borgoforte, and all simulations were conducted under steady flow conditions.

The parameterized GEV was exploited to generate synthetic flows of different lengths. These flows were then used as input into the HEC-RAS model to derive equal sizes of synthetic annual maximum levels. These water levels were assumed to be a typically observed sample that are usually available in any real application. To implement the common approach, the synthetic annual maximum water levels are converted into estimated annual maximum flows by using a rating curve. The study used the power-law relationship (Petersen-Øverleir, 2004) as the rating curve model. Also, since in any real application the parent model is not known a priori, the Gumbel distribution was selected as the fitting distribution and used to fit the estimated annual maximum flows and the estimation of a design peak flow. The estimated design peak flow is used as input to a hydraulic model to derive design flood levels. The Gumbel based design flood levels are compared with the true value and presented in terms of relative errors. The experiment was repeated 1000 times and for varying lengths, 30 50 and 100 years.

3.3 Statistical *versus* Hydrological methods of design flood estimation (Paper III)

The aim of this study was to evaluate the performance of two established methods of design flood estimation. The analysis was based entirely on four numerical experiments, with two experiments referring to statistical methods while the remaining two refer to hydrological methods.

The first step was to calibrate a weather and hydrological model, respectively, to available weather inputs and discharge record for a given catchment. A univariate Markovian weather model that was proposed by Richardson (1981) was adopted for this purpose while HBV (Bergström, 1992) served as the hydrological model. The calibrated models were considered as the true representations of the dominant processes present in the catchment. The calibrated weather model is used to compute a long synthetic sample of precipitation data that is used as input into a RR model to derive long synthetic sample of discharges by CS. A sample of annual maximum flows is created by extracting from the long synthetic discharge sample the highest discharge in each year. A series of design floods corresponding to different return periods are calculated using the Weibull plotting formula, and based on the sample of annual maximum flows.

The first two experiments refer to MS and MM, respectively, and implemented within the statistical method. The methodology adopted is the same as the method described in Section 3.1. The long sample of annual maximum flows is 10,000 years long. The long sample was split sequentially into 50 year chunks to create 200 samples that were used for implementing MS and MM.

The last two experiments are similar with the only difference being the choice of hydrological model used for CS. In this study, linear reservoir is used as a simple hydrological model. While HBV is used as complex hydrological model in the last experiment. Since HBV has already been adopted as the truth, this means that the last experiment only served as a benchmark to compare results.

The data for the last two experiments were prepared by splitting the long precipitation data into 50 year chunks to create 200 samples of precipitation data. For each precipitation data, and the corresponding 50 year discharge sample, the weather model (same as the true weather model) and a hydrological model were recalibrated. The recalibrated weather model is used to generate another set of long precipitation data that is fed into the recalibrated hydrological model to derive a long sequence of discharges by CS. The estimated design flood derived from the recalibrated hydrological model is compared to the estimate based on the true hydrological model (i.e. HBV). The results in this study were evaluated and presented in terms of relative errors.

3.4 Real world application of model selection and averaging (Paper IV)

The aim of this study was to apply the methodology developed in Papers I and III to a real flow record. An exceptionally long record of annual maximum flows recorded at Tiber River in Rome, Italy was collected to conduct this analysis. The record spans over a period of 500 years, and includes 185 years of systematic stage observation and 13 historical floods. When the water level is at 16 meters above the reference level (corresponding to 2550 m^3/s) major inundations were experienced at the Ripetta Landing in Rome (Calenda et al., 2005, 2009). The length of the flow record will allow for a robust estimation of the 100-year flood.

The available flow record was treated as a censored sample before it was used in estimating the 100-year flood. This estimate was purely based on the Tiber empirical distribution function. To make a reliable estimate of the 100-year flood, the systematic series is extended using information on historical floods. The return period of the 100-year flood was estimated by using the plotting formula proposed by Hirsh and Stedinger (1987) for censored samples.

Two subsamples were used to test MS, WMA and MM. These subsamples are referred to as modern series, spanning the period 1921 – 1989. The second sample is the systematic series (1782 -1989). The three techniques, MS, WMA and MM, and the distribution functions listed in Table 1 are used in analyzing the Tiber flow record. Bootstrapping is used in estimating measures of precision in terms of confidence intervals and standard errors.

4. Summary of papers

4.1 Paper 1. Estimating design floods with errors in the flow data

4.1.1 Motivation

The estimation of design floods typically involves the fitting of a probability distribution function to a record of annual maximum flows, and the fitted distribution is used to extrapolate the record to a flow magnitude corresponding to a given return period. The estimation process is known to be affected by different sources of uncertainties. For this reason, **Paper I** is focused on uncertainties arising from errors in the flow records, the choice of probability distribution function and sampling, i.e. the length of the flow record. These sources of uncertainties (and their effects) were evaluated in terms of relative based on numerical experiments and synthetic flow data. The design event in this study is the 100-year flood.

The main goal of **Paper I** is to compare the effects of MS, WMA and MM on design flood estimates. The hypothesis in this study is that an averaging of design flood estimates will lead to a more accurate and precise estimation compared to the estimate conditioned on a single best distribution function.

In different areas of forecasting such as economic, politics, and voting, the use of MM as a benchmark to compare other model averaging techniques is more or less a standard (Genre et al. 2013; Graefe et al. 2014, 2015). Thus its use in hydrology might be useful since it is both straightforward and easy to implement.

4.1.2 Results

Four different parameterizations of the Wakeby distribution (labeled as Wakeby-1, Wakeby-2, Wakeby-3, Wakeby-4 and Wakeby-5) were analyzed with Wakeby-1 selected as the parent with the highest value of skewness. Also, the five candidate probability distributions functions listed in Table 1 were fitted to synthetic flow data sampled from each of these four different parent distributions and the accuracy and variance of their estimates evaluated in **Paper I**. For the sake of achieving a clear structure in presentation style, only the results of Wakeby-1 are discussed in the thesis.

The values of the parameters of Wakeby -1 were taken from Landwehr et al. (1978). The results of the numerical experiments are presented in Figure 4.1 as boxplots. These boxplots compare the accuracies (including variance of errors) of design flood estimates based on different methods of dealing with uncertainty due to model choice, and estimates from individual distribution functions.

In Figure 4.1, the magnitude of observation errors β for a given sample size increases from the left to the right panels, while the sample size n for a given observation error increases from the top to the bottom panels. The boxplots show the distribution of the estimates when the experiment is repeated 1000 times. That is, 1000 synthetic flow samples are generated from the parent distribution and design flood estimation is conducted using each sample. In general, there is negative bias, i.e. a tendency towards underestimation, for all techniques, namely MS, WMA and MM, and the individual distribution functions when the parent is highly skewed. These underestimations is a result of information loss arising from fitting two or three parameter distributions to data derived from a parent distribution with five parameters. For an error magnitude of 15% and a sample size of 50 years, on average, WMA underestimates the true design flood by 19.6%, while MS and MM give an equal underestimation of 22.3%. The results when β equals 0% (i.e. no error in the flow data) serves as a benchmark to evaluate the performances of techniques and candidate distribution for different levels of error in the flow data.

The results also show that as the sample size increases, there is a corresponding decrease in variance for the three levels of error magnitude considered. Another conclusion from this study is that - since MS, MM and WMA yielded comparable results - there is more to be gained when model averaging is implemented. Averaging the design flood estimates derived from a range of candidate distributions allows the hydrologist to make use of the from the error that might arise from arbitrarily selecting a single distribution, or selecting a distribution based on some criterion such as AIC.

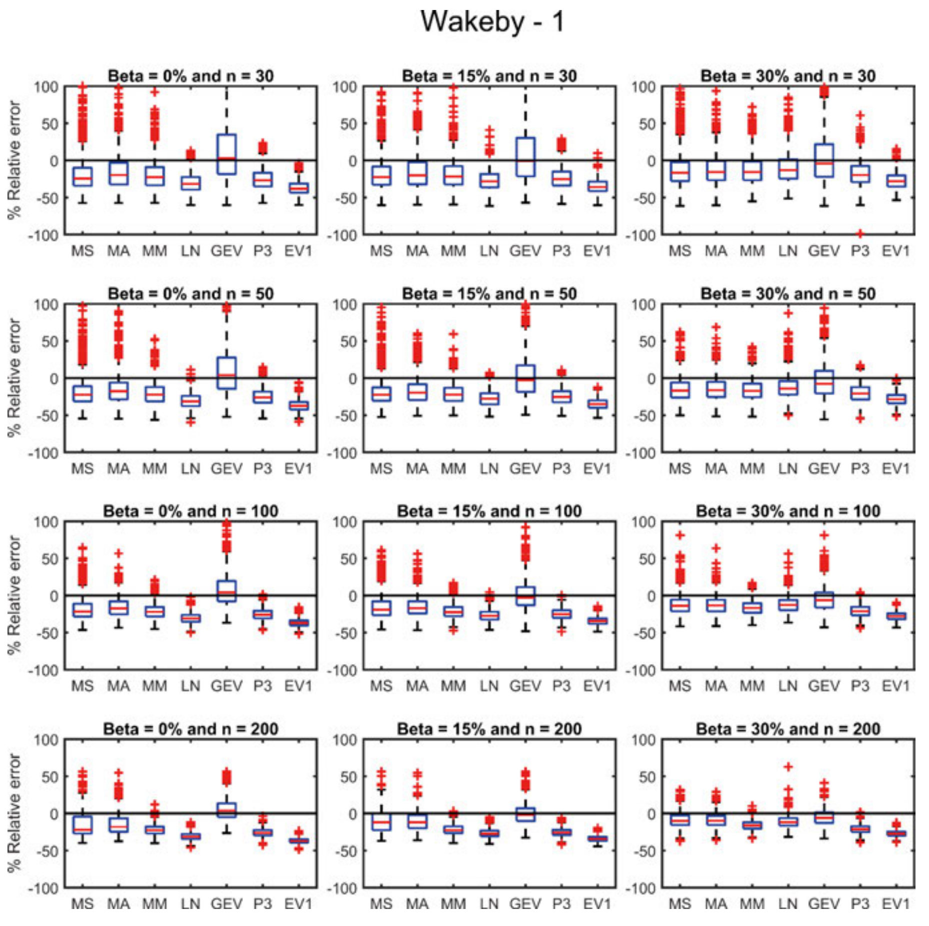


Figure 4.1. Boxplots of percentage relative error for MS, MA, MM and all candidate models, with Wakeby-1 as parent model. The red line represents the median (50th percentile) and the lower and upper end of the blue box represents the 25th and 75th percentile respectively. Outliers are represented by red crosses.

4.2 Paper 2. Comparing the performance of two alternative approaches for the estimation of design flood levels

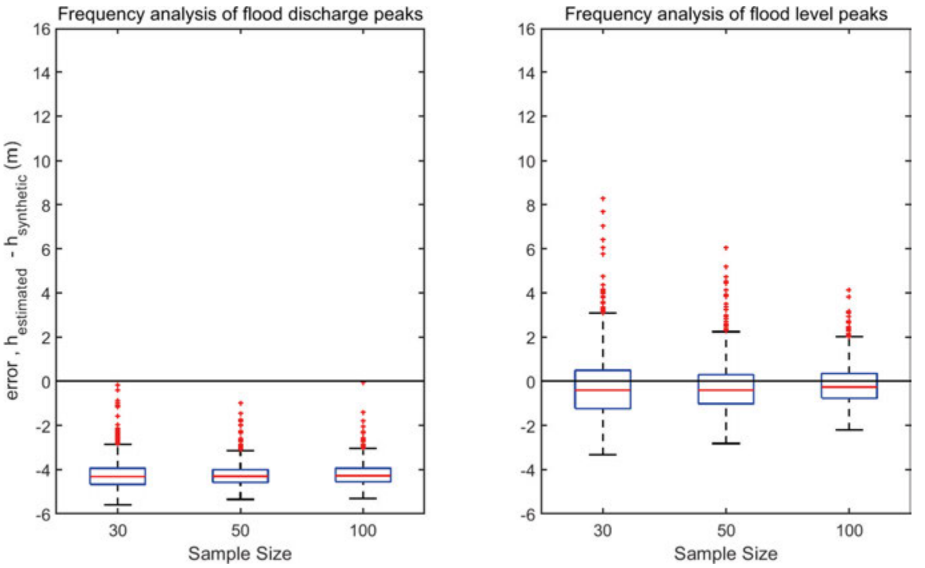
4.2.1 Motivation

The design of flood control measures requires the estimation of flood water levels corresponding to a given return period. The statistical method is the most common approach deployed to estimate these extreme flood events that the structural measures are designed to defend. The estimation typically requires three main steps. First, direct measurements of annual maximum water levels at a river cross-section are converted into annual maximum flows by using a rating curve. Second, a probability distribution function is fitted to these annual maximum flows to derive the design peak flow corresponding to a given return period. Third, the design peak flow is used as input to a hydraulic model to derive the corresponding design flood level. Each of these three steps contributes some degree of uncertainty in the estimated design flood levels.

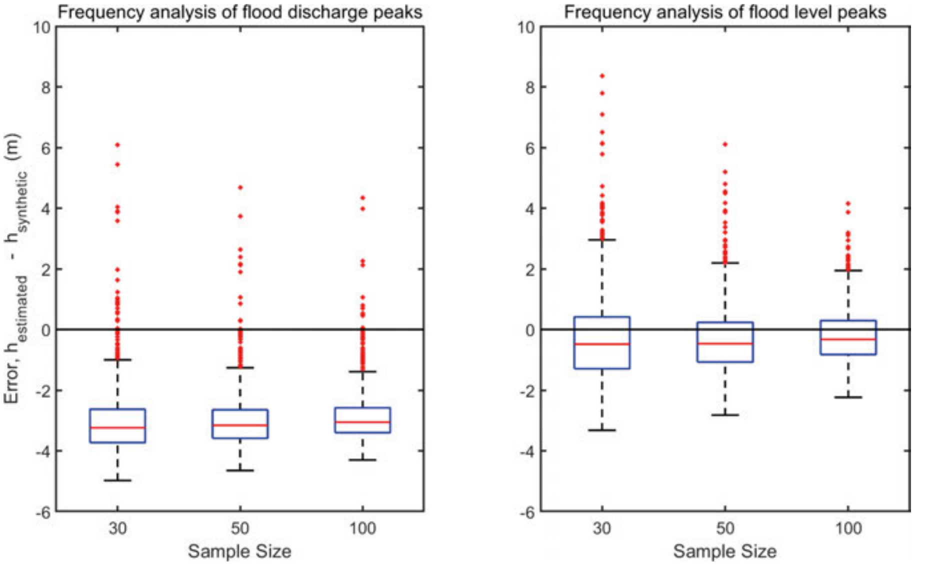
Paper II used a simulation framework to compare the common approach (i.e. based on the frequency analysis of annual maximum flows) with an alternative approach based on the frequency analysis of annual maximum water levels. The motivation behind this study is that high water levels are directly measured, and they often come along with less uncertainty than river flows. Also, frequency analysis on water levels is commonly applied in risk assessment studies for storm surge and coastal flooding (Xu et al. 2018; Chen et al. 2014; Razmi et al. 2017). However, and to the best-of-my-knowledge, the only related study is a technical note published by Dyhouse (1985) that demonstrates the application of frequency analysis of water levels to levee system design.

4.2.2 Results

The details of the methodology for this study is described in Section 3.2. Two river cross-sections (denoted as A and B) were selected for implementation. The cross-sections are 10 km apart and within the reach between Cremona and Borgoforte of the Po River in Italy. The results shown in Figure 4.2 suggest that frequency analysis of annual maximum water levels performed better in terms of accuracy and precision compared to the standard approach. The low performance of the common approach is due to the fact that it involves a cascade of three models – rating curve, probability distribution and a hydraulic model.



(A)



(B)

Figure 4.2 Boxplots of error estimates for the two approaches with Gumbel distribution used for design flood level estimation at cross-section **A** and **B**. The red lines represent the median (50th percentile), the lower and upper ends of the blue box represent the 25th and 75th percentile, respectively. Outliers are represented by red dots.

To be more specific, the plots suggests that the common approach resulted in 3m to 4m underestimation, on average, when both cross-sections are considered. On the contrary, the alternative approach had approximately 0.8m underestimation, on average, when both cross-sections are considered. These differences are quite substantial and would have an influence on flood defence design or risk assessment. Also, there is a more significant improvement in the precision for the alternative approach as sample size increases from 30 to 100 years. This is, however, only a specific example application that highlights the potential of the alternative approach. **Paper II** discusses in a more comprehensive way the pros and cons of the two approaches, and concludes that they should be considered as complementary.

4.3 Paper 3. Comparing statistical and hydrological methods for design flood estimation.

4.3.1 Motivation

When it comes to the estimation of design floods, statistical and hydrological methods are both well established in hydrology. The former method has faced some criticisms owing to the near lack of application of process understanding in the estimation process. The hydrological methods represent a shift towards providing a physical basis for the estimation problem. The shift has not been complete since in some countries design regulations for flood control projects still require the use of statistical methods. The main goal of **Paper III** is to develop a methodology to compare the design flood estimates based on these two methods. In this thesis, uncertainties arising from model choice (in both statistical and hydrological methods) were evaluated based on numerical experiments.

4.3.2 Results

The results of the four different experiments that were implemented in this study are shown in Figure 4.3. On the left panel, Boxplots A and B refer to two separate experiments within statistical method of design flood estimation. Experiment A is focused on estimates based on MS technique, and experiment B is about MM based estimations of the design flood. While on the right panel, Boxplots C and D refer to estimations based on simple (C) and complex (D) hydrological methods, in particular by CS. For return periods above 20 years, MS and MM lead to an underestimation of the design flood as the return period increases, on average. The variance of the errors are quit large for the MS estimates. This is as a result of the high frequency in the selection of GEV, which is shown in Figure 4.4 to have large errors as return period increases.

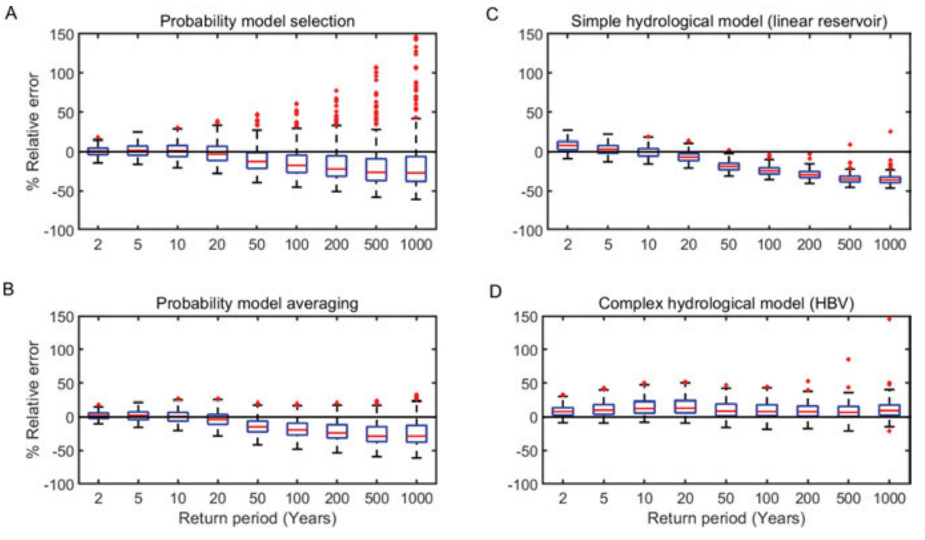


Figure 4.3 Boxplots show the precision of estimated design floods for different return periods and estimation methods.

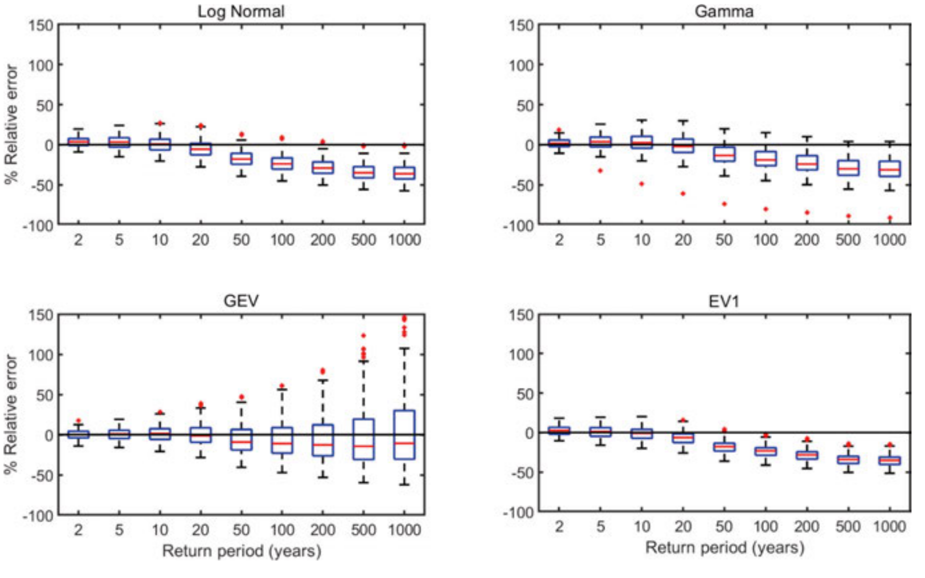


Figure 4.4 Accuracy and precision of the four candidate probability distributions used for design flood estimation.

The linear reservoir model experienced the same type of underestimation compared to statistical methods with the only difference that it had low variance in the error estimates. These results show the influence of the number of the parameters to be calibrated in a hydrological model. The results from panel D show the performance when the synthetic flows are fitted to the same model that was used for their generation. As for the previous experiments (**Paper II**), these outcomes are specific for our example application. **Paper III** discusses in a more comprehensive way the pros and cons of the two approaches, and concludes that they should be seen as complementary.

4.4 Paper 4. Evaluating the effects of model averaging versus model selection for design flood estimation based on real flow data.

4.4.1 Motivation

The aim of this study is to apply the methodology developed in **Papers I and III** to a real flow record. A long record of annual maximum flows recorded at Tiber River in Rome, Italy, was collected for this analysis. The record spans over a period of 500 years, and includes 185 years of systematic stage observations and 13 historical floods. The length of the record allowed for a robust estimation of the 100-year flood. Records of this length are rarely available to evaluate the estimate of the 100-year flood, which is always required in flood risk assessments.

4.4.2 Results

The 100-year flood was estimated to be 3224 m^3/s (Table 2) by extending the systematic series with the available historical floods. The estimated 100-year flood is treated as the true value since it was exceeded, on average, five times in the flow record. This form of 'temporal information expansion' is recommended by Merz and Blöschl (2008) for the robust estimation of return periods of flows available in a record. For the sake of comparison, the 100-year flood is estimated using the systematic series only and presented in Table 2. For this series, the 100-year flood is expected to fall between 3087 m^3/s (93-years) and 3106 m^3/s (186 years).

Table 2. Estimates of 100-year flood estimate based on plotting position formulae by Hirsh and Stedinger (1987) and Weibull plotting position.

Sample	Sample size	Sample Period	Design flood (m^3/s)	Plotting position
Extended series (1422 – 1989)	198	545	3224	Hirsh and Stedinger (1987)
Systematic series (1782 – 1989)	185	207	[3088, 3106]	Weibull

The effects of MS and WMA on design flood estimates were analyzed by making use of two subsamples (systematic and modern series).. Figure 4.5 shows a range of distribution fitted to the systematic and modern series, respectively.

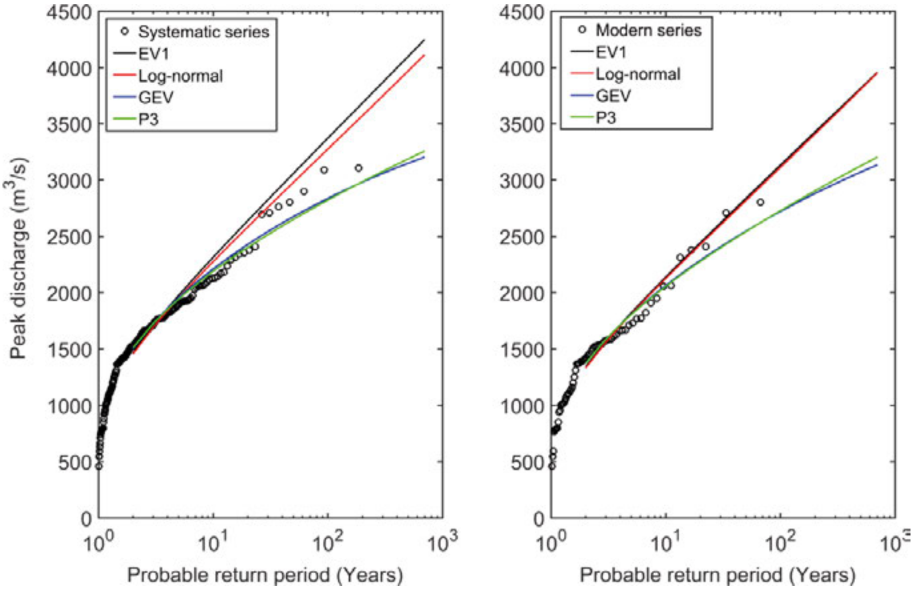


Figure 4.5 Plots of distributions fitted to systematic and modern series using maximum likelihood, and based on the Tiber Annual maximum flow record.

For the modern series, AIC and Akaike weights are estimated for all distribution functions considered. All the distribution functions have similar AIC values, including weights as shown in Table 3. As expected, the point estimates of individual distributions are quite varied. Since there is no clear identification of a best distribution function, and the design flood estimates vary quite reasonably among the distributions considered, we implemented a model average estimate as a way to deal with model choice uncertainty. The MM point estimate in the modern series is more robust compared to WMA even though the former overestimates the true design flood. In the systematic series shown in Table 4, MM and WMA underestimates the true design flood. However, the MM estimate is more robust since it represents a 5 % underestimation of the true value. The precision of all design flood estimates are estimated using the method of bootstrap and reported as confidence intervals and standard errors (S.E).

Table 3. Design flood estimates for all distributions and techniques based on the modern series (1921-1989)

Distributions	AIC	Δ_i	w	Design flood (m^3/s)	Confidence interval (m^3/s)	S.E (m^3/s)
Pearson 3	1006	0	0.28	2727	[2238, 3093]	563
GEV	1006	0	0.28	2720	[2356, 3076]	216
EV1	1006	0	0.28	3132	[2829, 3400]	177
Log-Normal	1007	1	0.16	3111	[2708, 3510]	247
WMA	-	-		2900	[2402, 3237]	358
MM	-	-		3897	[2945 , 4325]	338

Table 4. Design flood estimates for all distributions and techniques based on the systematic series (1782-1989).

Distributions	AIC	Δ_i	w	Design flood (m^3/s)	Confidence interval (m^3/s)	S.E (m^3/s)
Pearson 3	2822	0.50	0.50	2727	[2609, 3035]	347
GEV	2822	0.50	0.50	2720	[2641, 3017]	114
EV1	2831	9	0	3132	[3202, 3538]	103
Log-Normal	2833	11	0	3111	[3051, 3510]	145
WMA	-	-		2900	[2606, 3075]	291
MM	-	-		3076	[2836, 3342]	227

5. Concluding remarks

This thesis investigated the effects of different sources of uncertainty, ranging from errors in the flow data, length of sample and choice of distribution function (within the statistical method) or hydrological model (within the hydrological method) on design flood estimation. The analyses were conducted using synthetic and real flow data.

Below, the research outcomes in relation to the specific research objectives are reported.

The main contributions are as follows:

i. *Evaluating the consequences of errors in the flow data, length of sample and bias as a result of the choice of the distribution function (**Papers I, II, III, and IV**).*

Paper I shows that, for a highly skewed parent distribution (not rare in hydrology), commonly used distribution functions underestimate the design flood for all the magnitude of error in data and sample sizes considered. Secondly, MS and WMA (denoted as MA in **Paper I**) had almost the same performance in terms of accuracy and variance of errors in the estimate. MM had lower accuracy compared to MS and WMA but had the least variance for all sample sizes and magnitudes of errors considered. However, when the skewness of the parent distribution starts to reduce (i.e. moving from Wakeby-3 to Wakeby-5), the performance of these techniques (MS, WMA, MM) vary but not so much from what was observed from the highly skewed parent.

ii. *Developing a methodology to compare statistical and hydrological methods of design flood estimation (**Paper III**).*

A methodology is developed in **Paper III** to compare design flood estimates based on statistical and hydrological methods of flood estimation. The results of this study suggest that, for large return periods which are usually required in real applications, both statistical and hydrological methods lead to an underestimation of the design flood. However, the use of a simple hydrological model gave low variance in error estimates when compared to statistical methods. Within the statistical framework, model averaging (in this case MM) lead to low variance in errors compared to MS.

The following techniques, MS, WMA and MM were used in **Paper IV** to analyze the estimate of 100-year flood based on a real discharge record from the Tiber River in Rome, Italy. The results confirmed the findings from **Papers I & III**, which is that MA leads to more robust estimate of the design flood compared to MS. Secondly, MM out performed WMA in terms of accuracy in **Paper IV.**

iii. *Developing a methodology to compare flood frequency analysis based on records of annual flood levels versus records of annual maximum flows **(Paper II)**.*

A methodology was developed in **Paper II** to allow the comparison between flood frequency analysis based on annual maximum flows (i.e. the common approach) with flood frequency analysis of annual maximum water levels, for the estimation of design flood levels. The results from this study suggest that frequency analysis of annual maximum water levels performed better in terms of accuracy and precision compared to the standard approach. However, given the sensitivity of water levels to hydraulic effects (such as outfalls, vegetation and erosion) the potential of estimation design floods based on water levels seems to only apply to rivers with gentle slope and a stable channel geometry.

There are a number of caveats in this thesis. First of all, the study was based on the stationary assumption. Moreover, the number of experiments was limited. In order to generalize the findings, more distribution functions and different methods of parameter estimation (in both statistical and hydrological methods) are needed. The methodologies developed should also be tested using data from different climatic conditions. Further studies could also include the quantification of these sources of uncertainties within the framework of formal Bayesian inference methods (Viglione et al. 2013; Kavetski, 2018) or informal Bayesian techniques such as the GLUE method (Beven and Binley, 1992).

Finally, since the design flood is not known in advance in any real application, it is recommended to implement both statistical and hydrological methods of design flood estimation. As a matter of fact, these methods are based on consolidated theories, and have complementary advantages and limitations. As such, by following the precautionary principle (Foster et al., 2000), which calls for erring on the side of least consequences, one should get two (or more) design flood estimates based on alternative methods and then pick the maximum value among them. This approach will minimize the likelihood of underestimating the design flood, and therefore help support the development and planning of measures for flood risk reduction.

6. Sammafattning på svenska (Summary in Swedish)

En vanlig uppgift vid planering, design och hantering av olika typer av kontrollåtgärder för översvämningar är att uppskatta sannolikheten för extrema flöden i ett vattendrag, vilket ofta uttrycks som återkomstperioder. Dock så är vår nuvarande kunskap kring processer som leder till översvämningar begränsad, vilket kan leda till en hög osäkerhet kring det uppskattade flödet. För att lösa detta problem krävs det vanligtvis att följande fråga besvaras: *vad är sannolikheten att ett flöde av magnitud X återkommer eller överstigs i ett givet vattendrag; alternativt, givet en sannolikhet för att ett visst flöde inträffar, vad är dess magnitud (i.e. vad är det dimensionerande flödet)?* Två metoder som ofta används inom hydrologi för att hantera detta problem är den statistiska, respektive den hydrologiska, metoden. Den statistiska metoden har använts i drygt ett sekel, och har tillämpats vid utformning och ekonomisk utvärdering av olika åtgärder för att hantera översvämningsrisker. Med den statistiska metoden så anpassas en sannolikhetsfördelning till årliga maximala flöden, och för en vald återkomstperiod extrapoleras fördelningen för att ge motsvarande dimensionerande flöde. Olika typer av antaganden om fördelningen av flödesdata (en given fördelning eller flera olika fördelningar) har lett till utvecklingen av förhållandevis komplexa sannolikhetsfördelningar.

Till skillnad från den statistiska metoden så har den hydrologiska metoden främst funnit tillämpning inom forskningen, även om den även har använts kommersiellt vid t.ex. utvärdering av dammsäkerhet. Inom den hydrologiska metoden så tillämpas avrinningsmodeller för att simulera vattenföring i ett givet vattendrag med användning av nederbördsdata över det givna avrinningsområdet. Fördelen med den hydrologiska metoden är att den ger en möjlighet för användning av den senaste kunskapen kring processer som leder till översvämning. Eftersom att i stort sett alla typer av avrinningsmodeller kan användas så tolkas avrinningsmodellen som en hypotes rörande de huvudsakliga processerna involverade i översvämningar. Med den tekniska utvecklingen så har intresset för användandet av den hydrologiska metoden och avrinningsmodeller ökat, då längre simuleringar kan göras utan att vara allt för tidskrävande.

Det är sedan tidigare känt att de två ovanstående metoderna påverkas av flertalet osäkerhetskällor, exempelvis: fel som finns i inmatnings- och kalibreringsdata; partiska parameteruppskattningar som kan uppkomma genom olika metoder för parameteruppskattning, alternativt desinformation i, eller saknad av, insamlad data; olika modellstrukturer (d.v.s. användandet av olika sannolikhetsfördelningar eller avrinningsmodeller) som ger rimliga anpassningar till kalibreringsdata. Att fastställa hur dessa osäkerheter påverkar noggrannheten i uppskattningar av dimensionerande flöden är inte bara viktigt för hydrologisk forskning utan också för kommersiella tillämpningar.

I denna avhandling har problemet med uppskattning av dimensionerande flöden undersökts genom att jämföra två tekniker för att hantera osäkerhet som härrör från valet av de sannolikhetsfördelningar som används för extrapolering av flödesdata. Dessa två tillvägagångssätt är: (1) val av en specifik modell (MS, eng. *model selection*), där målet är att hitta den optimala sannolikhetsfördelningen från en samling av olika fördelningar. Generellt så används MS vid mer praktiska tillämpningar, exempelvis för att välja rätt modell för en specifik tillämpning. (2) Användandet av flera modeller (MA, eng. *model averaging*), där flertalet sannolikhetsfördelningar används för att uppskatta det dimensionerande flödet under antagandet att dessa tillsammans ger en mer robust uppskattning i jämförelse med att använda en enskild (specifik) sannolikhetsfördelning. MA används generellt då det är en större osäkerhet i de processer som leder till översvämning. Viktad MA (WMA, eng. *weighted model averaging*), och MA med lika vikt (eng. *equal weight averaging*; eller genomsnittet av flera modeller, MM, eng. *model mean*) är två tillvägagångssätt för MA som beaktades i denna avhandling. De två tillvägagångssätten implementerades med hjälp av ”Akaike Information Criterion” (AIC) vilket är baserad på informationsteori och uppskattar mängden information som går förlorad när en antagen sannolikhetsfördelning anpassas till data med en okänd sannolikhetsfördelning.

Ett problem vid uppskattningen av dimensionerande flöden är att det verkliga dimensionerande flödet generellt är okänt från start, vilket gör det svårt att systematisk utvärdera metoden som använts för att uppskatta det dimensionerande flödet. Ett sätt varmed detta problem bemöttes i den här avhandlingen (artikel I, II och III) var genom virtuella experiment, där en modell (statistisk eller hydrologisk) används varifrån parametrar och dimensionerande flöden betraktas som sanna och är kända i förväg. Därefter utvärderas felen mellan de sanna och de uppskattade värdena.

Påverkan av olika storleksordningar av fel, mängden insamlad data, samt användandet av MS eller MA, på uppskattningen av dimensionerande flöden studerades i artikel I, vilket baserades på numeriska experiment med syntetisk flödesdata härrörande från en antagen sannolikhetsfördelning. Fyra olika sannolikhetsfördelningar betraktades som möjliga för att anpassa de genererade flödena. Resultaten visade att MS och MA var nästintill likvärdiga beträffande noggrannhet och varians för att uppskatta det dimensionerande flödet. MM leder emellertid till varianser som är nästan samma som det mer komplexa WMA. Eftersom observationsfel i flödesdata vid översvämningar vanligtvis kommer från den avbördningskurva som används så jämfördes frekvensanalyser baserade på årliga maximala flöden (dvs. standardmetoden) med frekvensanalyser baserade på årliga maximala vattennivåer (artikel II), då målet är att uppskatta dimensionerande flöden vid översvämningar. Eftersom vattennivåer vanligtvis har minimala observationsfel, är direkt mätta samt enkla att mäta, så antogs det att uppskattningen av en dimensionerande vattennivå, snarare än ett dimensionerande flöde, skulle minska osäkerheten i de dimensionerande värdena. Statistisk analys av vattennivån, snarare än vattenflödet, är en standardmetod för att modellera översvämningar i kustområden, dock så finns det inga motsvarande studier för översvämningar av vattendrag. Resultaten från artikel II tyder på att frekvensanalys av maximala årliga vattennivåer var mer noggranna och hade en högre precision i jämförelse med standardmetoden. Standardmetodens låga prestanda beror dess sekventiella användande av tre olika modeller - avbördningskurva, sannolikhetsfördelning samt en hydraulisk modell.

Eftersom vissa forskare har kritiserat den statistiska metoden och argumenterat för användningen av den hydrologiska metoden för att uppskatta dimensionerande flöden så jämfördes de två tillvägagångsätten i artikel III. I denna artikel antogs en komplex hydrologisk modell som en korrekt beskrivning av de fysiska processerna och användes för att generera syntetiskt flödesdata. De syntetiska flödesdata för dimensionerande flöden användes i fyra experiment, två inom den statistiska metoden och ytterligare två inom den hydrologiska metoden. Resultaten visade att, för längre återkomstperioder, så var den statistiska metoden mer tillförlitlig i jämförelse med en enkel hydrologisk modell som användes som ett exempel i hydrologiska metoder. Dock så var variansen av fel baserat på den enkla hydrologiska modellen låg i jämförelse med den statistiska metoden för längre återkomstperioder.

De tre första artiklarna bygger på att utforska olika källor till osäkerheter och analysera deras inflytande på uppskattningar av dimensionerande flöden i anslutning till översvämningar. I den sista artikeln (artikel IV) så testades WMA och MM på en lång serie med uppmätta årliga maximal vattenföring i floden Tibern (Rom, Italien). Flödesdata från Tibern är unikt i den meningen att det sträcker sig över 500 år och möjliggör en robust uppskattning av 100-årsflödet. Resultaten från denna studie visar att MA leder till en mer robust uppskattning av det dimensionerande flödet i jämförelse med MS, samt att så var MM, som är lätt att implementera, mer tillförlitlig än WMA. Det finns således mer att vinna när en genomsnittlig uppskattning av det dimensionerande flödet används.

7. Acknowledgments

My experience from the beginning of my studies as a PhD student, to the point where I now have a complete PhD dissertation has been quite challenging. That I made it this far is because of the great deal of support from friends, family and colleagues. First, I will like to thank my main supervisor Giuliano. I am really grateful for offering me a PhD position, for your patience with me, the gentle push and support when things got critical, and for giving me the freedom to find my own path and interests when it comes to hydrology research. These and many more meant a lot to me, really, and looking back from our time in the Netherlands (as my masters thesis supervisor), I have realized how much you have influenced me both directly and indirectly. I must also mention that I have failed you in some aspects☺. I didn't become an avid runner. However, I still do occasional runs to please both you and myself. Secondly, I have not been a good protégé when it comes to socio-hydrology. Do you remember what happened during the Panta Rhei meeting at EGU 2018? Quite an embarrassment. I can already imagine you reading this and having a good laugh. Well, I am doing the same too☺.

I wish to thank my co-supervisors, Korbinian and Maurizio, for their huge support during the course of my PhD studies. Both of you have been my saving grace in so many situations such as, periods when Matlab decides to be a turn on my flesh, assisting in the preparation and reviews of my manuscripts etc. thank you so much! To my office mate Albin, I will miss you man. I have enjoyed our discussions on a wide range of topics. To Maryeh who was my office mate for a while, I've missed you, you're so kind and thanks for being a nice colleague and office mate. To Elisa, my most recent office mate, I really appreciate your sense of humor and jokes. The laughter they brought to me, especially during critical periods, were soothing to say the least☺. It has been five years since I joined the department and I have enjoyed the friendship of my colleagues; Bea, Lebing, Eduardo, Luigia, Reinert, Jean-Marc, Adam, Saba, Nino, Audrey, Kristina, Nina, Thomas Stevens, Agnes, Marc-Girons, Diana, Elena Mondino, Elena Ridolfi, Sara, Lucia, Faranak, Johanna, Martin, Maria, Vincent, Chiara, Claudia, Thomas Grabs, Peggy, Fatima and many more, thank you all for the discussions, parties and for just being amazing human beings.

I will also like to acknowledge Late Vit Klemeš who has influenced me during my PhD studies, and still do till date. Vit was a hydrologist and I came

across his articles in the year 2015. His first paper that I read was *"Dilettantism in Hydrology' Transition or Destiny?* That was followed by *"Tall tales about the tails of hydrological distributions (I)"* and then *"Statistics and Probability: wrong remedies for a confused hydrologic modeller"*. Vit wrote many articles and so many of them are quite technical: However, these three aforementioned articles are in my opinion his best pieces when it comes to his philosophical essays about hydrology. Vit (through his papers) set me on a path where I always talked about him and his ideas, as if I knew him personally. My behaviour was clearly that of a disciple. As a budding researcher, his writing style appealed to me a lot, especially how precise and incisive he can be with his arguments. It is always a delight when I go back and read the same papers, just so I can appreciate his arguments against the traditional approach to design flood estimation. I wish I had the privilege to meet him when he was alive. However, I sense he might not be happy with me, since after reading his papers, I still went on with fitting distribution functions to discharge records.

My gratitude goes to my siblings, Udodi, Adaobi and Junior. You guys have been so amazing with your love and support. I really love you guys. To my dad and mum, I am so grateful for the love, sacrifices and support that you both have made so that I can succeed in life. Thank you so much. Finally, to my darling wife Ubani. Thanks for being so patient, it's no mean feat. Your support, love and appreciation have pulled me through. I am forever in your debt.

References

Akaike, H., (1973). Information theory and an extension of the maximum likelihood principle. In: B.N. Petrov and F. Csáki, eds. *2nd International Symposium on Information Theory*, Tsahkadsor, Armenia, USSR, September 2–8, 1971, Budapest: Akadémiai Kiadó, 267–281.

Bárdossy, A., and Erich J. (1992) "Space-time model for daily rainfall using atmospheric circulation patterns." *Water resources research* 28.5: 1247-1259.

Bárdossy, A. (2007). Calibration of hydrological model parameters for ungauged catchments, *Hydrol. Earth Syst. Sci.*, 11, 703–710.

Bárdossy, A. (2008), Robust estimation of hydrological parameters, *Hydrol. Earth Syst. Sci.*, 12(6), 1273-1283.

Bergström, S. 1992. The HBV model – its structure and applications, SMHI Reports RH 4, Swedish Meteorological and Hydrological Institute (SMHI), Norrköping, Sweden.

Beven K, Kirkby MJ. (1979). A physically based, variable contributing area model of basin hydrology. *Hydrological Sciences Bulletin* 24:43–69.

Beven, K., & Binley, A. (1992). The future of distributed models: model calibration and uncertainty prediction. *Hydrological Processes*, 6, 279–298.

Beven, K., and I. Westerberg (2011), On red herrings and real herrings: Disinformation and information in hydrological inference, *Hydrol.Processes*, 25, 1676–1680, doi:10.1002/hyp.7963.

Beven, K. (2012), Causal models as multiple working hypotheses about environmental processes, C. R. *Geosci.*, 344, 77–88, doi:10.1016/j.crte.2012.01.005.

Beven, K. (2012). Rainfall - Runoff Modelling The Primer (2nd ed.). West Sussex: John Wiley & Sons.

Blöschl, G., Sivapalan, M., Wagener, T., Viglione, A., and Savenije, H. H. G. (Eds.): Runoff Prediction in Ungauged Basins – Synthesis across Processes, Places and Scales, Cambridge University Press, Cambridge, UK, 465 pp., 2013.

Bodo, B., & Unny, T. E. (1976). Model Uncertainty in Flood Frequency Analysis and Frequency Based Design. *Water Resources Research*, 12(6), 1109-1117.

Boughton W, Droop O. (2003). Continuous simulation for design flood estimation – a review. Environmental Modelling and Software 18: 309–318.

Burnham, K. P., & Anderson, D. R. (2002). MODEL SELECTION AND MULTIMODEL INFERENCE (Second ed.). New York: Springer.

Breinl, K. (2016). Driving a lumped hydrological model with precipitation output from weather generators of different complexity. *Hydrological Sciences Journal*, 61(8), 1395–1414.

Brandimarte, L., & Di Baldassarre, G. (2012). Uncertainty in design flood profiles derived by hydraulic modelling. *Hydrology Research*, 43(6), 753. http://doi.org/10.2166/nh.2011.086

Blazkova, S., & Beven, K. (1997). Flood frequency prediction for data limited catchments in the Czech Republic using a stochastic rainfall model and TOPMODEL. *Journal of Hydrology*, 195(1–4), 256–278. https://doi.org/10.1016/S0022-1694(96)03238-6

Buytaert, W., Bièvre, B. De, Wyseure, G., & Deckers, J. (2004). The use of the linear reservoir concept to quantify the impact of changes in land use on the hydrology of catchments in the Andes. *Hydrology and Earth System Sciences*, 8(1), 108–114.

Calenda, G., Mancini, C. P., & Volpi, E. (2005). Distribution of the peak floods of the Tiber River from the XV century. *Advances in Water Resources*, 615–625. http://doi.org/10.1016/j.advwatres.2004.09.010

Calenda, G., Mancini, C. P., & Volpi, E. (2009). Selection of the probabilistic model of extreme floods: The case of the River Tiber in Rome. *Journal of Hydrology*, 1–11. http://doi.org/10.1016/j.jhydrol.2009.03.010

Calver, A., & Lamb, R. (1995). Flood frequency estimation using continuous rainfall-runoff modelling. *Physics and Chemistry of the Earth*, 20(5–6), 479–483. https://doi.org/10.1016/S0079-1946(96)00010-9

Cameron, D. S., Beven, K. J., Tawn, J., Blazkova, S., & Naden, P. (1999). Flood frequency estimation by continuous simulation for a gauged upland catchment (with uncertainty). *Journal of Hydrology*, *219*(3–4), 169–187. https://doi.org/10.1016/S0022-1694(99)00057-8

Chen, Y., Huang, W., & Xu, S. (2014). Frequency Analysis of Extreme Water Levels Affected by Sea- Level Rise in East and Southeast Coasts of China. *Journal of Coastal Research*, (68), 105–112.

Cunnane, C., (1979). A note on the Poisson assumption in partial duration series models. *Water Resources Research*.,15(2), 489–494.

Cheng, L. and AghaKouchak, A., (2014). Nonstationary precipitation intensity-duration-frequency curves for infrastructure design in a changing climate. *Scientific Reports*, 4, 7093. doi:10.1038/srep0793

Di Baldassarre, G., Laio, F., and Montanari, A. (2009). Design flood estimation using model selection criteria. *Physics and Chemistry of the Earth*, Parts A/B/C, 34(10–12), 606–611. http://doi.org/10.1016/j.pce.2008.10.066

Di Baldassarre, G., Laio, F., and Montanari, A. (2012). Effect of observation errors on the uncertainty of design floods. *Physics and Chemistry of the Earth*, 85–90.

Di Baldassarre, G., and Montanari, A. (2009). Uncertainty in river discharge observations: a quantitative analysis. *Hydrology and Earth System Sciences* Discussions, 6(1), 39–61. http://doi.org/10.5194/hessd-6-39-2009

Dyhouse, G. R. (1985). STAGE-FREQUENCY ANALYSIS AT A MAJOR RIVER JUNCTION. *Journal of Hydraulic Engineering*, *111*(4). http://doi.org/https://doi.org/10.1061/(ASCE)0733-9429(1985)111:4(565)

Fisher, R., & Tippett, L. (1928). Limiting forms of frequency distribution of the largest or smallest member of a sample. *Mathematical Proceedings of the Cambridge Philosophical Society*, 24, 180–190.

Foster K.R., Vecchia P., Repacholi, M.H. (2000). Risk management. Science and the precautionary principle. *Science* ;288(5468):979–981.

Fréchet, M. (1927). Sur la loi de probabilité de l'écart maximum. *Annales de la Société Polonaise de Mathématiques,* 6,93–126.

Fuller, W.E., (1914). Flood flows. *Trans. Am. Soc. Civ. Eng*., 77, 564 – 617.

Gaume, E. (2018). Flood frequency analysis: The Bayesian choice. *WIREs Water*, 5(4), e1290. https://doi.org/10.1002/wat2.1290

Genre, V., Kenny, G., Meyler, A., & Timmermann, A. (2013). Combining expert forecasts: can anything beat the simple average? International Journal ofForecasting, 29(1), 108–121.

Graefe, A., Armstrong, J. S., Jones, R. J., Jr., & Cuzán, A. G. (2014). Combining forecasts: an application to elections. International Journal of-Forecasting, 30(1), 43–54.

Graefe, A., Kuchenhoff, H., Stierle, V., & Riedl, B. (2015) Limitations of Ensemble Bayesian Model Averaging for forecasting social science problems. International Journal of Forecasting, 31, 943 – 951.

Grimaldi, S., Petroselli, A., Arcangeletti, E., Nardi, F., (2013). Flood mapping in ungauged basins using fully continuous hydrologic-hydraulic modeling. *Journal of Hydrology*, 487: 39-47. DOI:10.1016/j.jhydrol.2013.02.023

Grimaldi, S., Petroselli, A., Serinaldi, F., (2012). Design hydrograph estimation in small and ungauged watersheds: continuous simulation method versus event-based approach. *Hydrological Processes*, 26(20): 3124-3134. DOI:10.1002/hyp.8384

Hashimoto, T., J. R. Stedinger, and D. P. Loucks (1982), Reliability, resiliency, and vulnerability criteria for water resource system performance evaluation, Water Resour. Res., 18(1), 114–120, doi:10.1029/WR018i001p00014.

Hazen, A. (1914). ‘‘Storage to be provided in impounding reservoirs for municipal water supply.’’ *Trans. ASCE*, ASCE, New York, 77, 1539–1640.

Hirsch, R. M., & Stedinger, J. R. (1987). Plotting position for historical floods and their precision. *Water Resources Research*, 23(4), 715-727.

Höge, M., Guthke, A. and Nowak, W. (2019) The hydrologist’s guide to Bayesian model selection, averaging and combination. *Journal of Hydrology*, 96-107. https://doi.org/10.1016/j.jhydrol.2019.01.072

Kavetski D. (2018) Parameter Estimation and Predictive Uncertainty Quantification in Hydrological Modelling. In: Duan Q., Pappenberger F., Thielen J., Wood A., Cloke H., Schaake J. (eds) Handbook of Hydrometeorological Ensemble Forecasting. Springer, Berlin, Heidelberg.

Kobierska, F., Engeland, K. and Thorarinsdottir, T. (2018) Evaluation of design flood estimates – a case study of Norway. *Hydrology Research*, 49(2): 450-465. https://doi.org/10.2166/nh.2017.068

Klemeš, Vit. (2000). TALL TALES ABOUT TAILS OF HYDROLOGICAL DISTRIBUTIONS. I. *Journal of Hydrologic Engineering*, 1(July), 227–231. https://doi.org/10.1061/(ASCE)1084-0699(2000)5:3(232)

Koutsoyiannis, D. (2010). HESS Opinions "A random walk on water", *Hydrol. Earth Syst. Sci.*, 14, 585-601, https://doi.org/10.5194/hess-14-585-2010

Kuczera, G. (1992). Uncorrelated Measurement Error in Flood Frequency Inference. *Water Resources Research*, 28(1), 183–188.

Lamb, R. (2005) Rainfall-Runoff Modelling for Flood Frequency Estimation in: Anderson, M.G. and McDonnell J.J. (eds), *Encyclopedia of Hydrological Sciences*, Wiley, London.

Lamb, R., Faulkner, D.,Wass, P. & Cameron, D. (2016). Have applications of continuous rainfall–runoff simulation realized the vision for process-based flood frequency analysis?. *Hydrological Processes,* 30(14), 2463 – 2481. https://doi.org/10.1002/hyp.10882

Landwehr, J. M., Matalas, N. C., & Wallis, J. R. (1980). Quantile Estimation With More or Less Floodlike Distributions. *Water Resources Research* , 16(3), 547–555.

Merz, R., & Blöshl , G. (2008). Flood Frequency Hydrology: 1. Temporal, spatial, and causal expansion of information. *Water Resources Research* 44(8), W08432, doi:10.1029/2007WR006744.

Mulvaney, T.J. (1851). On the use of self-registering rain flood gauges, in Making Observations of the Relation of Rainfall and Flood Discharges in a Given Catchment, *Proc. Inst. Civil Eng. Ireland,* vol.4, pp. 18-31, Institute of Civil Engineering of Ireland, Dublin.

Moran, P. A. P. (1957). The statistical treatment of flood flows. Transactions, American Geophysical Union, 38(4), 519–523. https://doi.org/10.1029/TR038i004p00519

Obeysekera, J., and Salas, J. (2014). Quantifying the Uncertainty of Design floods under Nonstationary Conditions. *Journal of Hydrologic Engineering* 19(7):1438-1446, DOI: 10.1061/(ASCE)HE.1943-5584.0000931

Okoli, K., Breinl, K., Brandimarte, L., Botto, A., Volpi, E., Di Baldassarre G. (2018). Model averaging versus model selection: estimating design floods with uncertain river flow data. *Hydrological Science Journal*, 63(13-14): 1913-1926.

Pathiraja, S., Westra, S., and Sharma, A. (2012). Why constinuous simulation? The role of antecedent moisture content in design flood estimation, *Water Resources Research*, 48(6), 1-15. doi:10.1029/2011WR010997,

Petersen-Øverleir, A. (2004). Accounting for heteroscedasticity in rating curve estimates. *Journal of Hydrology*, *292*(1–4), 173–181. http://doi.org/10.1016/j.jhydrol.2003.12.024

Razmi, A., Golian, S., & Zahmatkesh, Z. (2017). Non-Stationary Frequency Analysis of Extreme Water Level: Application of Annual Maximum Series and Peak-over Threshold Approaches. *Water Resources Management*, *31*(7), 2065–2083. http://doi.org/10.1007/s11269-017-1619-4

Read, L.R. and Vogel, R.M. (2015). Reliability, return periods, and risk under nonstationarity. *Water Resources Research*, 51(1), 6381-6398.

Richardson, C.W., (1981). Stochastic Simulation of Daily Precipitation, Temperature, and Solar-Radiation. *Water Resources Research,* 17(1): 182-190. DOI 10.1029/Wr017i001p00182

Rogger, M., Pirkl, H., Viglione, A., Komma, J., Kohl, B., Kirnbauer, R., Merz, R. and Blöschl, G. (2012). Step changes in the flood frequency curve: process controls. *Water Resources Research,* 48(5), 1 – 15. doi:10.1029/2011WR011187, 2012

Rogger, M., Kohl, B., Pirkl, H., Viglione, A., Komma, J., Kirnbauer, R., Blöschl, G. (2012). Runoff models and flood frequency statistics for design flood estimation in Austria - Do they tell a consistent story? *Journal of Hydrology*, 456–457, 30–43. https://doi.org/10.1016/j.jhydrol.2012.05.068

Rossi F., Fiorentino M. and Versace P. (1984) Two component extreme value distribution for flood frequency analysis. *Water Resources Research*, 20(7), 847–856. https://doi.org/10.1029/WR020i007p00847

Seibert, J. and Vis, M. J. P. (2012). Teaching hydrological modeling with a user-friendly catchment-runoff-model software package, *Hydrol. Earth Syst. Sci.,* 16, 3315–3325, https://doi.org/10.5194/hess-16-3315-2012, 2012

Salas, J. D., Obeysekera, J., & Vogel, R. M. (2018). Techniques for assessing water infrastructure for nonstationary extreme events: a review. *Hydrological Sciences Journal*, 63(3), https://doi.org/10.1080/02626667.2018.1426858.

Strupczewski, W. G., Singh, V. . P., & Feluch, W. (2001). Non-stationary approach to at-site flood frequency modelling I . Maximum likelihood estimation. *Journal of Hydrology*, 248, 123–142.

Tarasova, L., Merz, R., Kiss, A., Basso, S., Blöschl, G., Merz, B., & Fischer, S. (2019). Causative classification of river flood events. Wiley Interdisciplinary Reviews: *Water*, e1353.

Viglione, A., Merz, R., Salinas, J. L., & Blöschl, G. (2013). Flood frequency hydrology: 3. A Bayesian analysis. *Water Resources Research,* 49(2), 675–692. http://doi.org/10.1029/2011WR010782

Volpi, E. (2019). On the return period and probability of failure in hydrology WIREs Water, 6(3), e1340. https://doi.org/10.1002/wat2.1340

Westerberg, I. K., & McMillan, H. K. (2015). Uncertainty in hydrological signatures. *Hydrology and Earth System Sciences* , 3951–3968. http://doi.org/10.5194/hess-19-3951-2015

Winter, B. Schneeberger, K., Dung, N. V., Huttenlau, M., Achleintner S., Stötter, J., Merz, B., & Vorogushyn S., (2019). A continuous modelling approach for design flood estimation on sub-daily time scale. *Hydrological Science Journa*l. DOI:10.1080/02626667.2019.1593419

Xu, S., & Huang, W. (2008). Frequency analysis for predicting 1% annual maximum water levels along the Florida coast, US. *Hydrological Processes*, *22*, 4507–4518. http://doi.org/10.1002/hyp.7051 Frequency

Acta Universitatis Upsaliensis

Digital Comprehensive Summaries of Uppsala Dissertations from the Faculty of Science and Technology 1832

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".)

Distribution: publications.uu.se
urn:nbn:se:uu:diva-390362

ACTA
UNIVERSITATIS
UPSALIENSIS
UPPSALA
2019