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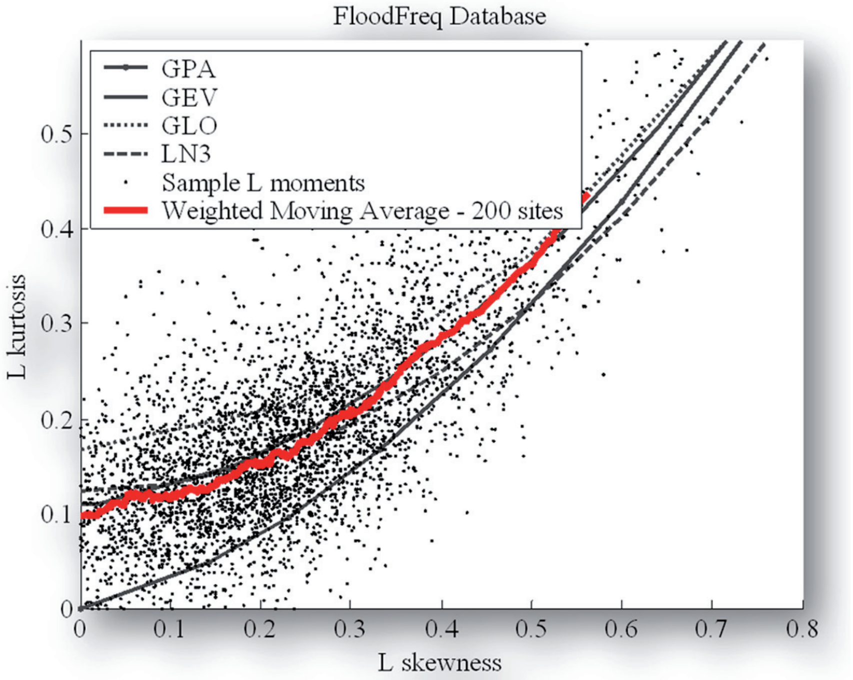
FLOODFREQ COST Action ES0901

European Procedures for Flood Frequency Estimation



REVIEW OF APPLIED-STATISTICAL METHODS FOR FLOOD-FREQUENCY ANALYSIS IN EUROPE

WG2

cost
EUROPEAN COOPERATION
IN SCIENCE AND TECHNOLOGY

Centre for
Ecology & Hydrology
NATURAL ENVIRONMENT RESEARCH COUNCIL

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Abstract

Flood frequency analysis is used for establishing a relationship between flood magnitude and frequency of occurrence (return period) and for estimating the design-flood at a given location of interest. The approach can be implemented locally (At-Site Flood Frequency Analysis, SFFA); or regionally (Regional Flood Frequency Analysis, RFFA), which is used to limit unreliable extrapolation when available data record lengths are short as compared to the recurrence interval of interest, or for predicting the flooding potential at locations where no observed data are available. Both SFFA and RFFA are mature disciplines and consolidated methodologies are available for many European regions. As a result, different European countries, and sometimes even different regions within a country, have adopted different methodologies, which are often selected on the basis of traditional approaches or restricted due to limitation of available data.

The main objective of the COST Action ES0901 European procedure for flood frequency estimation (FloodFreq, http://www.cost-floodfreq.eu/), which started in 2010, is to undertake a pan-European comparison and evaluation of methods for flood frequency estimation under the various climatologic and geographic conditions found in Europe, and different levels of data availability, as required by European Flood Directive (2007/60/EC). In particular, Working Group 2 (WG2) is focusing on an assessment of statistical methods for flood frequency estimation. In the first phase of WG2, state-of-the-art methods were collected from all member countries of the WGs, and presented in a report form.

In this report, the description of applied frequency analysis methods is presented. The report also include a catalogue of flood data availability/unavailability across Europe together with relevant information (e.g., catchment descriptors, climatological [see above] and hydrological characteristics, indications on frequency distribution recommended for use in flood frequency studies) are collected and presented. Finally, this report presents some preliminary outcomes of analyses that aim to identify in an L moment-based framework the most suitable parent distributions for representing the frequency regime of annual maximum flood across Europe.

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1. Introduction

1.1. General Background

Reliable estimates of extreme flood events are required for the design and operation of vital infrastructures and also for more general flood risk management and planning. This information is generally obtained through the use of flood frequency estimation techniques. These techniques are based upon the principle of statistical analyses of series of observed flood events, providing estimates of the likely magnitude of future extreme events through extrapolation. Unsurprisingly, extreme flood events are seldom observed locally, and hydrologists have little or no chance of gathering an adequate sample of catastrophes for analysis. This raises the question of how best to extrapolate to extreme events when no or only short series of recent events are available.

1.2. COST Action ES0901 FloodFreq

While the occurrence of extreme floods is a shared problem across Europe, no standardised European approach to flood frequency estimation exists. The main objective of COST Action ES0901 (FloodFreq) is to undertake a pan-European comparison and evaluation of methods of flood frequency estimation under the various climatologic and geographic conditions found in Europe, and different levels of data availability. A scientific framework for assessing the ability of these methods to predict the impact of environmental change on future flood frequency characteristics (flood occurrence and magnitude) will be developed and tested. The findings of the Action will be disseminated as a set of guidelines for professionals involved in flood management in Europe.

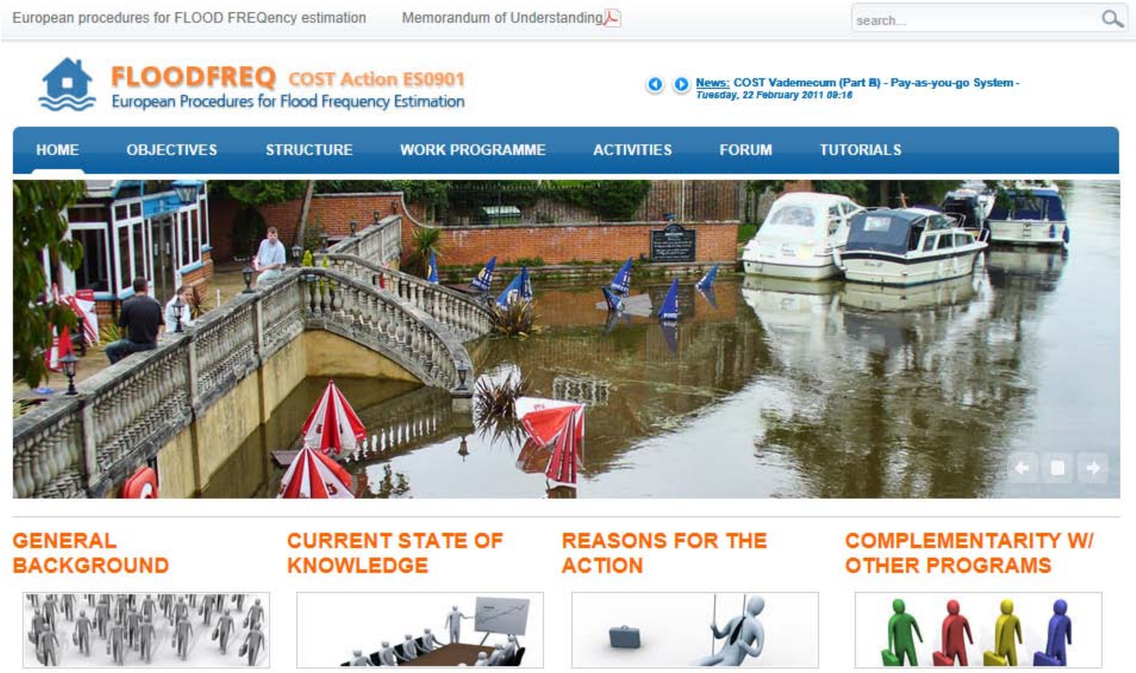
FloodFreq is relying on the involvement of geographically dispersed participants, namely: Austria, Belgium, Bulgaria, Cyprus, Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Latvia, Lithuania, Netherlands, Norway, Poland, Serbia, Slovakia, Slovenia, Spain, Turkey, United Kingdom as well as representation from South Africa, South Korea and the World Meteorological Organisation).

In order to ensure effective communication, co-ordination and dissemination, a dedicated and interactive website is hosted and maintained throughout the duration of the Action. The web page is accessed at the address: www.cost-floodfreq.eu (Figure 1.1).

1.3. Working Groups

The scientific work is carried out by five (5) working groups (WG). The main tasks of each working group are listed below:

- WG1: Inventory of data and methods and compilation of benchmark datasets
- WG2: Assessment of statistical methods for flood frequency estimation
- WG3: Use of rainfall-runoff models for flood frequency estimation
- WG4: Impact of environmental change on flood frequency estimates
- WG5: Dissemination of results



News: COST Vademecum (Part B) - Pay-as-you-go System - Tuesday, 22 February 2011 09:16

Figure 1.1 Welcome page of FloodFreq website.

1.4. WG1 and WG2

Flood frequency analysis is used for estimating the design-flood at a given site / location. The approach can be implemented locally (At-Site Flood Frequency Analysis, SFFA), or regionally (Regional Flood Frequency Analysis, RFFA). RFFA is used to limit unreliable extrapolation when available data record lengths are short as compared to the recurrence interval of interest, or for predicting the flooding potential at locations where no observed data are available. Despite the maturity of SFFA and RFFA and the existence of consolidated methodologies available for many European regions, scientific progress continues and there is a constant need to evaluate the gains obtained from new methods over existing knowledge.

Different European countries (and sometimes even different regions within a country) adopt different methodologies. Also, methodologies are often selected on the basis of traditional choices or what is known to work well for a limited number of local catchments, rather than on an objective assessment of available methods. FloodFreq addresses this disconnected picture, promoting a pan-European and synergistic approach to flood frequency analysis as required by European Floods Directive (2007/60/EC). FloodFreq aims at homogenizing and harmonizing the current level of knowledge on the approach to flood frequency analysis through a comprehensive application and verification across Europe of methodologies proposed by the scientific community.

WG1 and WG2 are working together in order to bring together the data and methods of flood data analysis used in Europe and assess the statistical methods for flood frequency estimation.

1.5. Structure of the Report

This report brings together the available and relevant information used in flood frequency studies across Europe. In particular, it catalogues, at national level, (a) the flood data sets, and (b) the catchment descriptors corresponding to the data sets and the methods used for flood frequency analysis. It also presents analysis of data supplied for data series of flood events.

The report presents the flood frequency information supplied by the WG2 members concerning the methods used in each country, including the availability of relevant flood and catchment data, case studies, and plans for future development.

A significant effort was devoted to the compilation of a pan-European database of Annual Maximum Series (AMS) of flood flows. Data from a total of 4,105 sites (i.e. 162,813 station-years of data of annual maximum series) have been sourced from 13 countries during the Action. In addition, this report briefly presents and discusses some preliminary analyses that have been performed in a L moment framework (see e.g. Hosking and Wallis, 1997) to identify the most suitable parent distribution at a European level.

2. Summary of reports

2.1. Flood data availability

Flood data availability varies considerably between the 18 member countries of COST Action ES0901 (FloodFreq) participating in WG2. In seven countries a national flood database is readily available in digital form, consisting of Annual Maximum Series (AMS) and/or Partial Duration Series (PDS) of daily mean data and/or instantaneous flood peak data (also see Table 2.1 and Figures 2.1, 2.2).

Nationwide flood datasets can be derived in four additional countries for which daily or higher resolution data are available. In Lithuania access to data is limited and only for use by local institutions. In Turkey data are available for purchase, and in Cyprus data are available but need to be digitized. No data are publicly available in Bulgaria and Greece, while in Hungary information on data availability was not supplied. Series of instantaneous flood peak data is available or can be derived or purchased in nine countries and in one country is available for local usage only. Daily or higher resolution data is available in eight countries, which means that in these countries any type of flood series, i.e. AMS, PDS and seasonal series, can be derived.

Table 2.1 Flood data availability[1] among the COST Action members (X: readily available, P: possible to derive from available data, L: limited availability / available only for local studies, N: not available).

	AMS		PDS				
	Inst. Flood Peak	Daily discharge (or other timescale)	Inst. Flood Peak	Daily discharge (or other timescale)	Other available Data	Time period	Seasonal
Austria	X	X	P	P	Daily or higher resolution	ca 1960-today	P
Belgium	P	P	P	P	Daily or higher resolution	ca 1985-today	P
Bulgaria	N	N	N	N			
Cyprus	L*	L*	L*	L*	L*		
Denmark	X	X	N	N			
Finland	N	P	N	P	Daily data	varying	P
France	N	X	N	N			
Germany	X*	X*	N	N			
Greece	N	N	N	N			
Hungary	N	N	N	N			

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[1] *As a general rule: for the majority of the countries with available data, availability does not imply public availability. It is an agreed policy in the Action that shared data FROM ALL COUNTRIES are for use within COST Action ES0901 (FloodFreq) and not made publicly available.*

	AMS		PDS				
	Inst. Flood Peak	Daily discharge (or other timescale)	Inst. Flood Peak	Daily discharge (or other timescale)	Other available Data	Time period	Seasonal
Italy	X	X	P*	P*	30-min data*	ca 1920-today	P*
Lithuania	L	L	N	N			L
Norway	P*	P	P*	P	Daily or higher resolution	varying - today	P
Poland	P*	P*	N	P*	Daily data; monthly peaks		L
Slovakia	X	N	N	N		varying	X*
Spain	X*	X	N	P	Daily data		P
Turkey	X*	X*	P*	P*	Daily data*	ca 1935-today	P*
UK	X	X	X	P	Daily data	varying	P

	Notes to Table 2-1
Austria	
Belgium	Most stations have hourly or 15-min time scale; Data are available, but some not readily (should be collected from different authorities)
Bulgaria	No data available
Cyprus	* Data are available in year books but not digitally
Denmark	
Finland	
France	
Germany	* Data available separately for the federal states
Greece	No data available
Hungary	
Italy	*upon request; Until 1993 flood data were validated and published by a National Service (SIMN), after by regional districts (ARPA) - time periods vary according to the considered district.
Lithuania	
Norway	*For some stations and time periods
Poland	*limited availability of all data
Slovakia	*only for a few stations and short periods; Data are provided by the Slovak Hydrometeorological Institute
Spain	*For some stations and time periods
Turkey	Inst. Flood Peak data (AMS readily available; PDS possibly to be derived from daily records) for purchase (AMS and daily discharge (yearbooks) data (hardcopies) of the recording period 1935-2000 available at the project partner institute – available for Action use)
UK	http://www.environment-agency.gov.uk/hiflows/91727.aspx; http://www.ceh.ac.uk/data/nrfa/index.html

Figure 2.1 FloodFreq countries - WG2 members only - (thick black borders), and coverage of Annual Maximum Series (AMS) of flood flows at a national level (red areas).

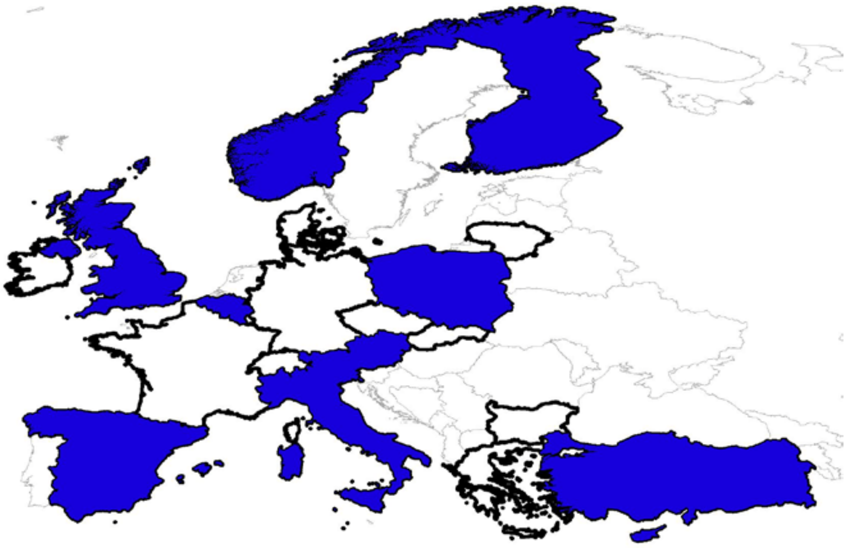

Figure 2.2 FloodFreq countries - WG2 members only - (thick black border), and coverage of Partial Duration Series (PDS) of flood flows at a national level (blue areas).

Table 2.2 Catchment descriptor availability[2] among the COST Action members (x-y-coord: streamgauge latitude and longitude; z: streamgauge altitude a.s.l.; A: catchment area; Aimp: impervious percentage of drainage area; Hmax-mean-min: highest, mean and minimum catchment elevation; MAP: mean annual precipitation; Reserv: presence of reservoirs; T: mean annual temperature; R: mean annual runoff; Soils: HOST soils data).

	x-coord	y-coord	z	A	Aimp	Hmax	Hmean	Hmin	MAP	Reserv.	T	R	Soils	Remarks[3]
Austria	X	X	X	X		X	X	X	X	X	X	X		Available, but not public
Belgium	X	X	X	X	X	X	X	X	X					To be collected from different authorities
Bulgaria														No info on descriptors from the report
Cyprus	X	X	X	X	X	X	X	X	X	X	X	X	X	
Finland	X	X	X	X					X	X				Both percentage of lakes and reservoirs
France	X	X	X	X										
Germany	X	X	X	X	X	X	X	X	X	X	X	X	X	X: For the federal states of BB, BW, BY, HE, MV, RP, SN, ST and SH.
Greece														No info on descriptors from the report
Italy	X	X	X	X	X	X	X	X	X	X		X		
Lithuania	X	X	X	X	X	X	X	X	X	X				
Norway	X	X	X	X	X	X	X	X	X	X	X	X		T can be calculated.
Poland	X	X		X										4-scale code and “remarks” for factors affecting runoff altering the natural flow
Slovakia	X	X	X	X		X	X	X	X		X	X		Available, but not public
Spain	X	X		X	X	X	X	X	X	X				
Turkey	X	X	X	X		X	X	X	X					Available, but not public
UK	X	X		X	X		X		X	X			X	

Table 2.2 shows the availability of the most common catchment descriptors within the countries involved in the COST Action. It is noticeable that only the most elemental catchment properties (such as gauge location and altitude, elevations, drainage area) are readily available in all the countries. It is worth remarking that most of these catchment descriptors can be retrieved or estimated from DEM (Digital Elevation Model) processing, by analysing pan-European gridded datasets (e.g. Climatic Research Unit CRU Pan-european

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[2] *As a general rule: for the majority of the countries with available data, availability does not imply public-availability. It is an agreed policy in the Action that shared data FROM ALL COUNTRIES are for use within COST Action ES0901 “FloodFreq” and not publicly available.*

[3] *Other descriptors are available for the countries listed in Table 2-2 (e.g, Norway % glacier; % urban area; % above tree line; % forest, % agricultural area, % effective lake, % bog, river and catchment gradient, river length). The table considers only the most diffuse ones.*

rainfall data; Joint Research Centre JRC Eusoils http://eusoils.jrc.ec.europa.eu/; CORINE land-cover http://www.eea.europa.eu/data-and-maps/data/corine-land-cover-2006-raster-1; etc.), in GIS (Geographic Information System) environments. Meteorological variables like mean annual temperature and mean annual precipitation are available (or can be calculated/obtained indirectly) in almost all the countries, but more specific descriptors like soil properties or percentage of impervious area are available nationwide only in a few countries.

2.2. Availability of Flood Frequency Analyses at National Level

Nationwide flood frequency analysis studies are available in nine countries (e.g., Figure 2.3). In Germany reference studies are available at the level of the federal states and in Belgium for the Flemish part only. The public agencies and institutions of six countries provide indications as to the most suitable parent distributions to be used for flood frequency analysis, but in general these indications appear to be sparse. In a number of countries the Generalized Extreme Value (GEV, see e.g., Hosking and Wallis, 1997) distribution is among the recommended choices (e.g., Austria, Germany, Italy, Spain), but a variety of 2- or 3-parameter distributions are also used (e.g., EV1 or Gumbel distribution, Generalized Pareto, GPA, 3-parameter LogNormal, LN3, etc.) depending on the region. National research studies on flood frequency have been carried out or are in progress in 10 countries (see Table 2.3).

Figure 2.3 FloodFreq countries - WG2 members only - (thick black border), and coverage of Flood Frequency Analysis performed at a national level (green areas).

2.3. Availability of Regionalization Studies at National Level

The application of regionalization approaches for estimation of design discharges at scarcely gauged and ungauged sites has been reported from 12 countries (see Figure 2.4). The most commonly used regionalization scheme is the delineation of fixed regions, most commonly on the basis of prevailing geographical, hydrological and climatic conditions. Variations of this general approach have been applied in Belgium, Germany, Greece, Italy, Lithuania, Poland, Slovakia and Spain; it has also been tested in Turkey.

Cluster analysis (see e.g. Burn, 1989) has been used for the pooling of catchments in Italy, Norway, Slovakia and Germany, where the regionalization scheme differs between Federal states. The Region of Influence (ROI, Burn, 1990) approach has been applied in Italy and UK. It has also been tested in Slovakia, but not yet adopted in practice. Top-kriging, as a novel geostatistical method (Merz et al., 2005; Skøien et al., 2006, Skøien and Blöschl, 2007), has been used for estimation of design discharges in Austria; it has also been tested recently in other countries (see Table 2.4). Cyprus, Finland and France have not reported the use of regional approaches in engineering practice.

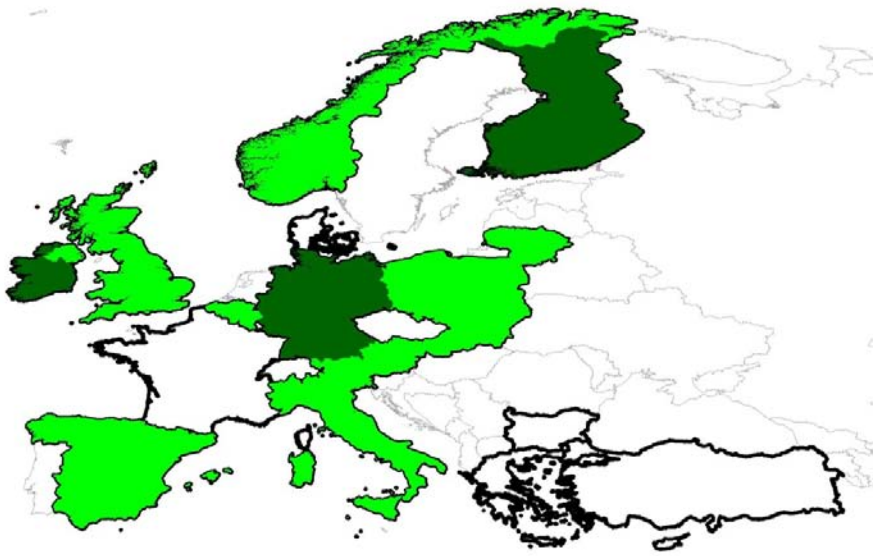

Figure 2.4 FloodFreq countries - WG2 members only - (thick black border), and coverage of Flood Frequency Analysis performed at a national level (dark green areas) together with Regionalization studies (light green).

Table 2.3 National FFA and RFFA studies availability among the COST Action members (X: available; N: not available; GEV: Generalized Extreme Value distribution; EV1: Gumbel or extreme value distribution type I; TCEV: Two-Component Extreme Value distribution; GPA: Generalized Pareto distribution).

			AMS	PDS		
	National analysis	Use of regionalisation	Standard parent distr.	Standard parent distr.	National research studies	Notes
Austria	X	X	GEV		X	
Belgium	X*	X		GPA	N	*for Flemish part
Bulgaria						No info
Cyprus	N	N	N	N	N	
Denmark						
Finland	X	N	EV1	N	N	
France	N	N	N		N	
Germany	*	*	GEV[1]		X	[1]in BY, HE, SH
Greece	N				N	No data available
Hungary						
Italy	X	X	GEV, TCEV		X	
Lithuania	X	X	N		X	
Norway	X	X	N	N	X	
Poland	X	X	N		X	
Slovakia	X	X	N		X	
Spain	X	X	EV1, GEV, TCEV*		X	*depending on region
Turkey					ongoing	
UK	X	X			X	

Table 2.4 Availability of RFFA studies among the COST Action members and approaches adopted for the regionalization of hydrological information (HIE stands for “hierarchical approach”; nested regions and clusters, see e.g. Gabriele and Arnell, 1991).

	Fixed Geographical Regions	Cluster A. (climatic)	Cluster A. (hydrol.)	Focused Pooling (ROI)	Other	Notes
Austria					Geostat.(Top-Kriging)	
Belgium			X (3)			Only for Flemish region
Bulgaria						No indication in the report
Cyprus						No regional approach
Finland						No regional approach
France						No regional approach
Germany	X	X	X			Regionalisation depends on the federal state
Greece	X					North-western part of Greece
Italy	HIE	X	X	X		Regionalisation studies based on AMS of instantaneous and daily flows. Cluster analysis and ROI applied locally
Lithuania	X (3)					
Norway		HIE				Separate for annual, snow-melt and autumn floods; only used for ungauged sites and without nearby observations
Poland	X (4)					
Slovakia	X	X	X	X		Fixed geographical regions and cluster analysis preferred
Spain	X (36)					Regions based on geographical conditions
Turkey			X			Regionalisation for microregion in Turkey
UK				X		Only used for ungauged sites and without nearby observations. Site similarity measure based on standard annual average rainfall and three catchment descriptors

3. Flood data

3.1. FloodFreq streamflow database

During the first year of implementation of FloodFreq, the main effort of WG2 was the compilation of a pan-European database of flood flows observations. The preliminary assessment of flood data availability at national level for various European countries involved in the Action revealed that annual maximum series (AMS) of flood flows are the most widespread standard (see Figures 2.1 and 2.2). Therefore it was decided to focus on a collection of AMS of flood flows considering daily flows, as well as instantaneous peak flows where available.

Table 3.1 illustrates the main characteristics of the national AMS datasets available in the database. Due to national policies and regulations that restrict the publication of some of these data, the flood data themselves were summarized into statistical moments. In particular, the assembled annual flood series were characterised by sample length N and L moments of orders from 1 (i.e., sample mean) to 5, i.e. l_1, l_2… l_5 (see Hosking and Wallis, 1997 for an introduction on L moments). The use of L moments instead of conventional moments offers several advantages such as the possibility of characterizing a wider range of distributions, smaller bias and higher robustness of the estimators when applied to short samples (see e.g., Hosking and Wallis, 1997). FloodFreq database consists therefore in the following information: N, l_1, l_2… and l_5.

3.2. Preliminary analysis: L moment ratio diagrams

The flood data available in the database are summarised and visualised using L-moment diagrams, as recommended by Hosking and Wallis (1997), Vogel and Fennessey (1993) and Peel et al. (2001) and others, for use in guiding the selection of the most suitable 3-parameter parent distribution of the flood data. Each diagram shows the ratio between l_4 and l_2 (L coefficient of kurtosis, or L kurtosis) plotted against the ratio between l_3 and l_2 (L coefficient of skewness, or L skewness).

Table 3.1 FloodFreq streamflow database: number of sites and station-years of data[4] for the FloodFreq annual sequences.

Country		**Sites**	**Station-years of data**	**Kind of data**
AT	Austria	676	28592	Instantaneous
CY	Cyprus	9	382	Daily
DE	Germany	415	22516	Daily
DK	Denmark	43	2789	Daily
FR	France	1172	45331	Instantaneous
IE	Ireland	215	6708	Instantaneous
IT	Italy	373	8207	Instantaneous
LT	Lithuania	30	1953	Daily
NO	Norway	104	3120	Daily
PL	Poland	39	3426	Instantaneous
SK	Slovakia	174	7995	Instantaneous
SP	Spain	220	8594	Instantaneous
UK	United Kingdom	635	23200	Instantaneous
FloodFreq		**4105**	**162813**	

In particular, Figures 3.1 to 3.13 present sample L moment ratios (dots) country-wise, together with weighted moving averages (WMA, red lines) computed on the basis of moving windows of various widths, where the width was selected to be the minimum of either 40 sites or half the number of sites in the country. The moving average weights sample L moment ratios proportionally to the length of each sample. Theoretical relationships between L skewness and L kurtosis for 3-parameters distributions that are commonly used in RFFA (namely: Generalized Logistic GLO, Generalized Pareto GPA, 3-parameter Lognormal LN3, and Generalized Extreme-Value GEV) are also shown in the diagram. The figures enable one to detect the most suitable 3-parameter distribution by comparing the theoretical relationships with WMA's.

GEV, LN3 and GLO are generally the most suitable distributions for the various nations included in the dataset. The GPA distribution is in general inappropriate, which was an expected result as the FloodFreq database includes annual maximum sequences, while GPA has been shown to be mostly suitable for representing the frequency regime of partial duration series (e.g. Madsen and Rosbjerg, 1997; Stedinger *et al.*, 1993). Moreover, under the assumptions that the arrival of peaks over a threshold follows a Poisson process and that the peaks themselves are GPA distributed, it can be shown that the annual maximum values follow a GEV distribution (Hosking and Wallis, 1987; Stedinger *et al.*, 1993; and Madsen *et al.*, 1997).

Figure 3.14 reports all WMAs in a single diagram and shows that the GEV distribution is generally the most suitable one. This result is even clearer in Figure 3.15, which reports the sample L moment ratios for the entire FloodFreq database together with a WMA computed on the basis of 200 sites.

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[4] Instantaneous: annual maximum instantaneous flood peak
Daily: annual maximum daily discharge

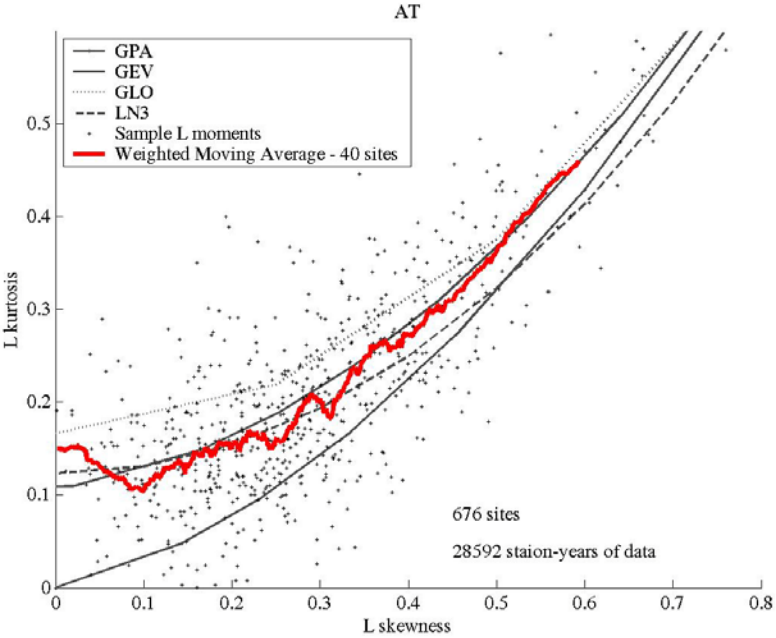

Figure 3.1 L moment ratio diagram for **AUSTRIA** (AT): sample L moment ratios (dots), together with weighted moving averages (WMA, red lines), weighting sample L moment ratios proportionally to the length of each sample; theoretical relationships between L skewness and L kurtosis for some 3-parameters distributions: Generalized Logistic GLO, Generalized Pareto GPA, 3-parameter Lognormal LN3, and Generalized Extreme-Value GEV.

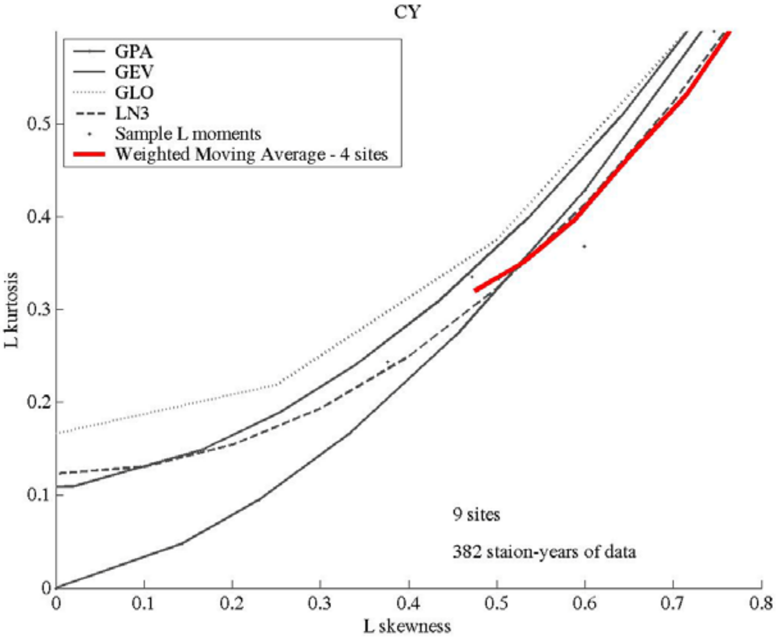

Figure 3.2 L moment ratio diagram for **CYPRUS** (CY): sample L moments (dots), together with weighted moving averages (WMA, red lines), weighting sample L moments proportionally to the length of each sample; theoretical relationships between L skewness and L kurtosis for some 3-parameters distributions: Generalized Logistic GLO, Generalized Pareto GPA, 3-parameter Lognormal LN3, and Generalized Extreme-Value GEV.

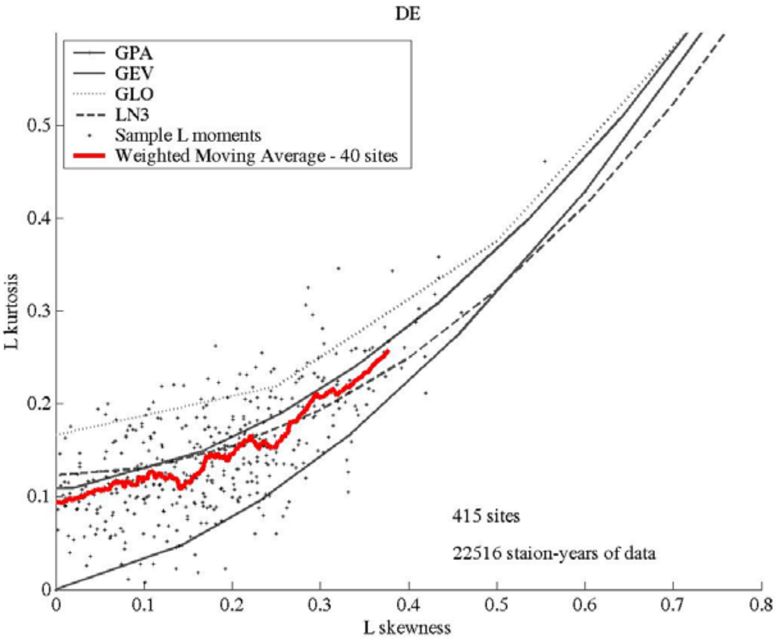

Figure 3.3 L moment ratio diagram for **GERMANY** (DE): sample L moment ratios (dots), together with weighted moving averages (WMA, red lines), weighting sample L moments proportionally to the length of each sample; theoretical relationships between L skewness and L kurtosis for some 3-parameters distributions: Generalized Logistic GLO, Generalized Pareto GPA, 3-parameter Lognormal LN3, and Generalized Extreme-Value GEV.

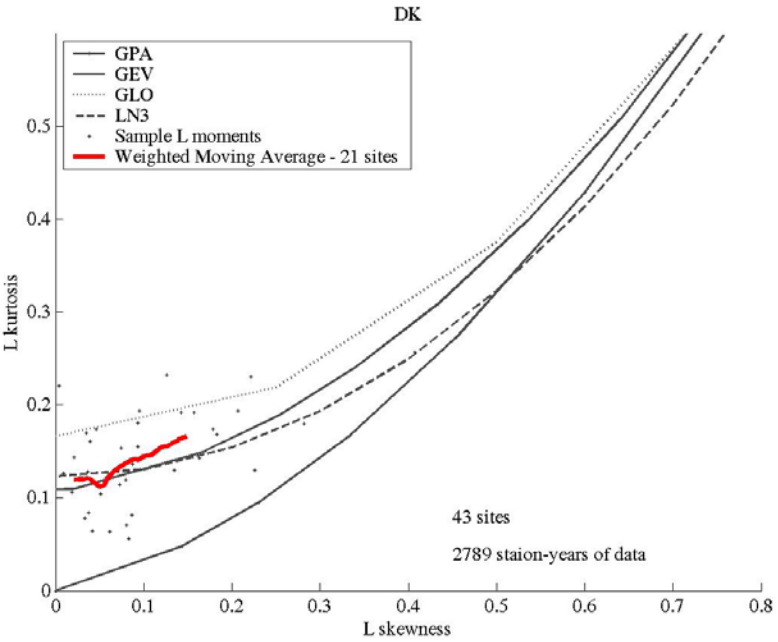

Figure 3.4 L moment ratio diagram for **DENMARK** (DK): sample L moment ratios (dots), together with weighted moving averages (WMA, red lines), weighting sample L moments proportionally to the length of each sample; theoretical relationships between L skewness and L kurtosis for some 3-parameters distributions: Generalized Logistic GLO, Generalized Pareto GPA, 3-parameter Lognormal LN3, and Generalized Extreme-Value GEV.

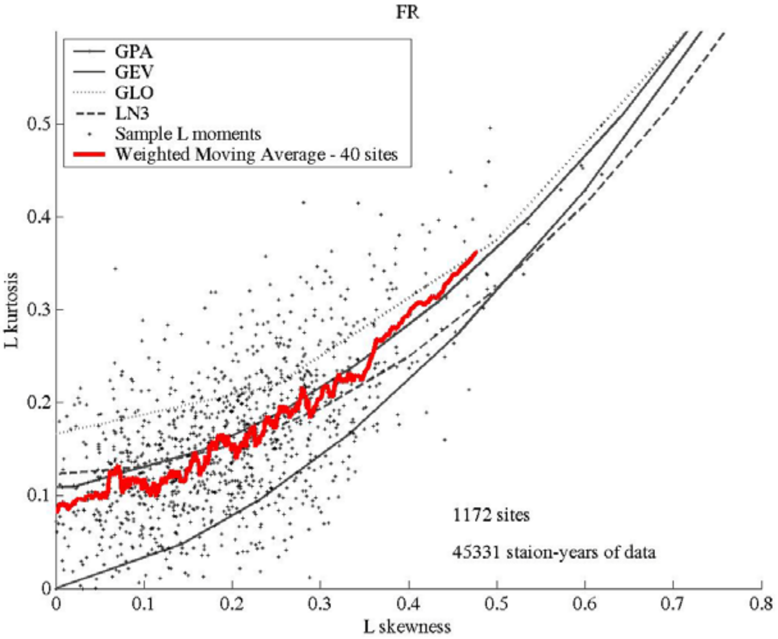

Figure 3.5 L moment ratio diagram for **FRANCE** (FR): sample L moment ratios (dots), together with weighted moving averages (WMA, red lines), weighting sample L moments proportionally to the length of each sample; theoretical relationships between L skewness and L kurtosis for some 3-parameters distributions: Generalized Logistic GLO, Generalized Pareto GPA, 3-parameter Lognormal LN3, and Generalized Extreme-Value GEV.

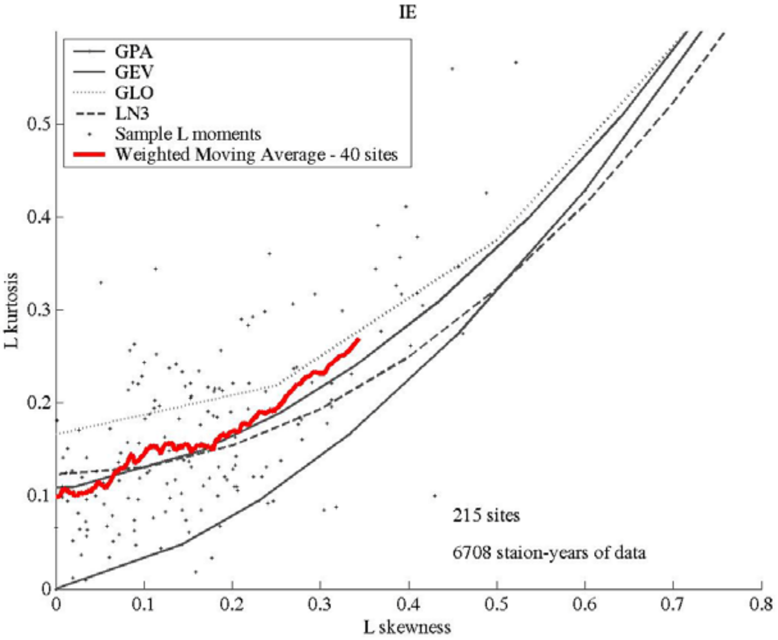

Figure 3.6 L moment ratio diagram for **IRELAND** (IE): sample L moment ratios (dots), together with weighted moving averages (WMA, red lines), weighting sample L moments proportionally to the length of each sample; theoretical relationships between L skewness and L kurtosis for some 3-parameters distributions: Generalized Logistic GLO, Generalized Pareto GPA, 3-parameter Lognormal LN3, and Generalized Extreme-Value GEV.

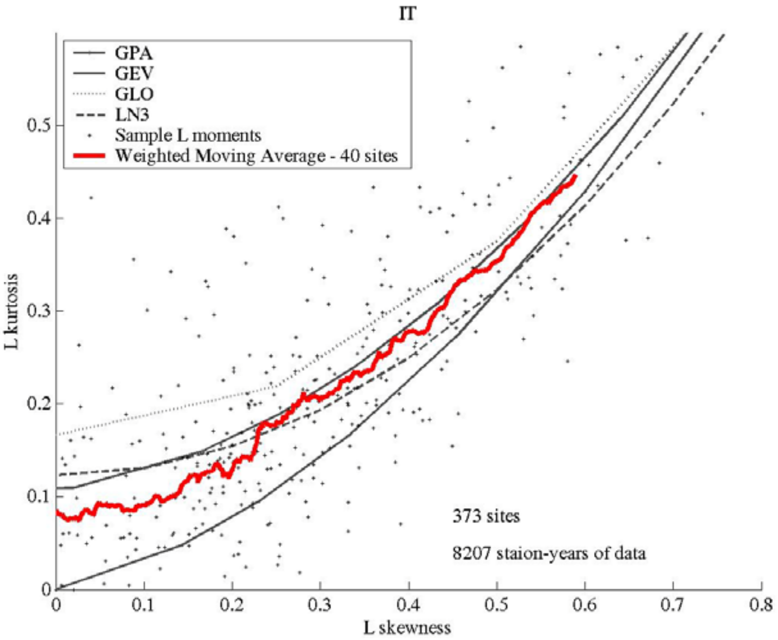

Figure 3.7 L moment ratio diagram for **ITALY** (IT): sample L moment ratios (dots), together with weighted moving averages (WMA, red lines), weighting sample L moments proportionally to the length of each sample; theoretical relationships between L skewness and L kurtosis for some 3-parameters distributions: Generalized Logistic GLO, Generalized Pareto GPA, 3-parameter Lognormal LN3, and Generalized Extreme-Value GEV.

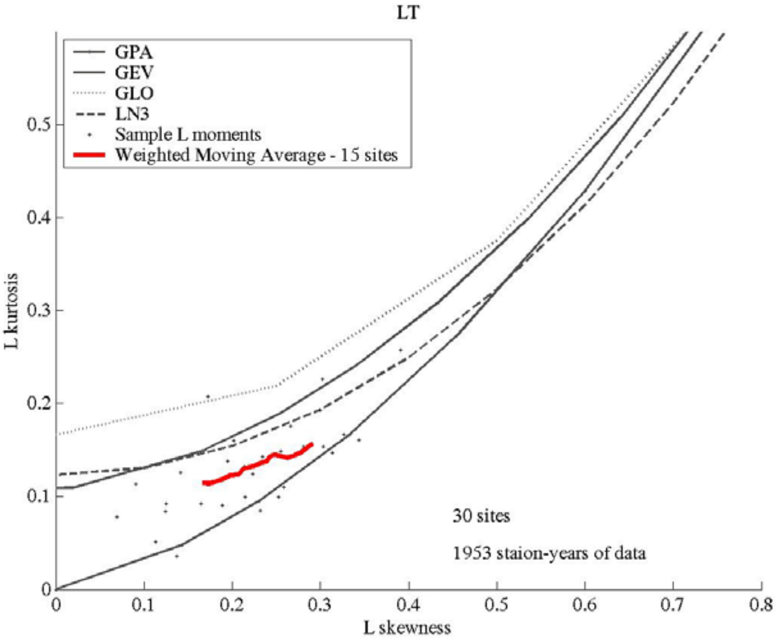

Figure 3.8 L moment ratio diagram for **LITHUANIA** (LT): sample L moment ratios (dots), together with weighted moving averages (WMA, red lines), weighting sample L moments proportionally to the length of each sample; theoretical relationships between L skewness and L kurtosis for some 3-parameters distributions: Generalized Logistic GLO, Generalized Pareto GPA, 3-parameter Lognormal LN3, and Generalized Extreme-Value GEV.

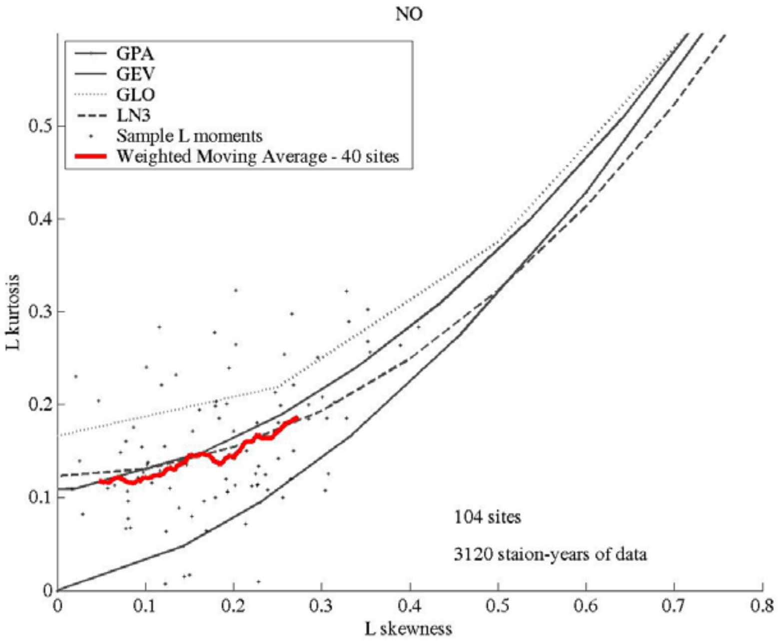

Figure 3.9 L moment ratio diagram for **NORWAY** (NO): sample L moment ratios (dots), together with weighted moving averages (WMA, red lines), weighting sample L moments proportionally to the length of each sample; theoretical relationships between L skewness and L kurtosis for some 3-parameters distributions: Generalized Logistic GLO, Generalized Pareto GPA, 3-parameter Lognormal LN3, and Generalized Extreme-Value GEV.

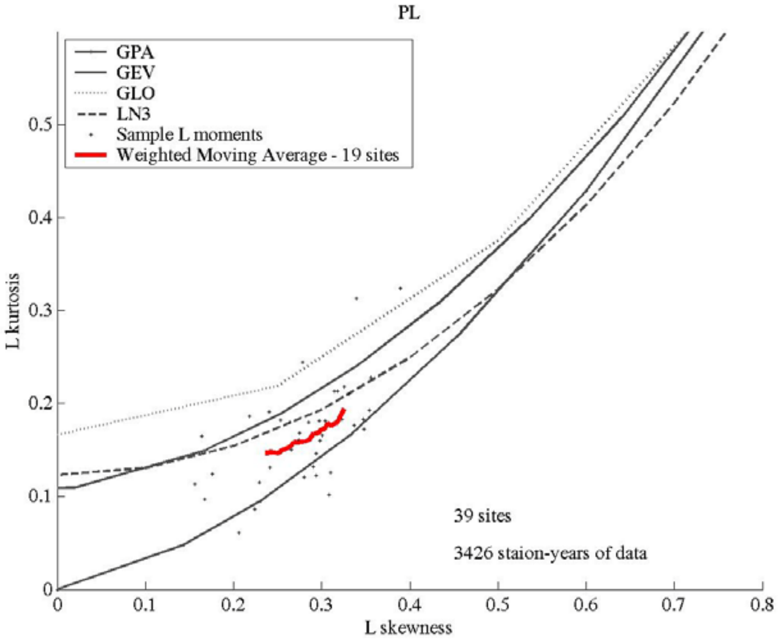

Figure 3.10 L moment ratio diagram for **POLAND** (PL): sample L moment ratios (dots), together with weighted moving averages (WMA, red lines), weighting sample L moments proportionally to the length of each sample; theoretical relationships between L skewness and L kurtosis for some 3-parameters distributions: Generalized Logistic GLO, Generalized Pareto GPA, 3-parameter Lognormal LN3, and Generalized Extreme-Value GEV.

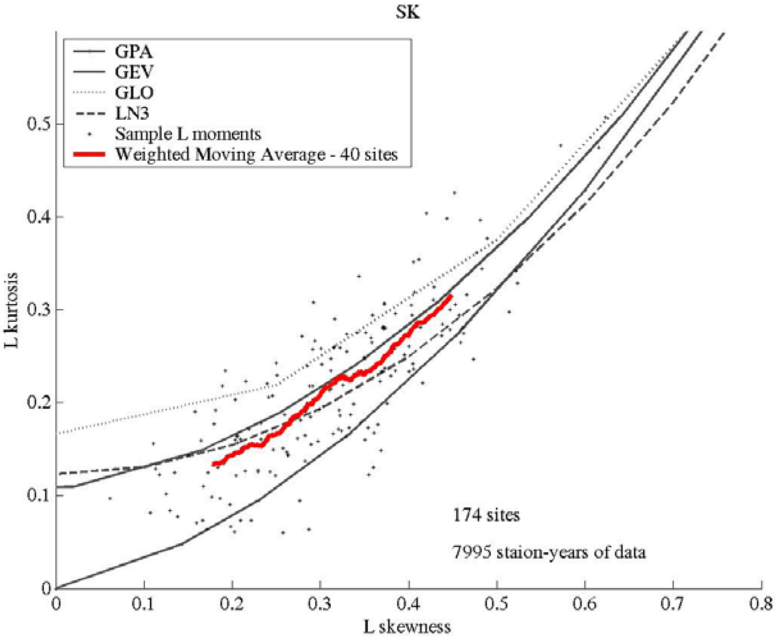

Figure 3.11 L moment ratio diagram for **SLOVAKIA** (SK): sample L moment ratios (dots), together with weighted moving averages (WMA, red lines), weighting sample L moments proportionally to the length of each sample; theoretical relationships between L skewness and L kurtosis for some 3-parameters distributions: Generalized Logistic GLO, Generalized Pareto GPA, 3-parameter Lognormal LN3, and Generalized Extreme-Value GEV.

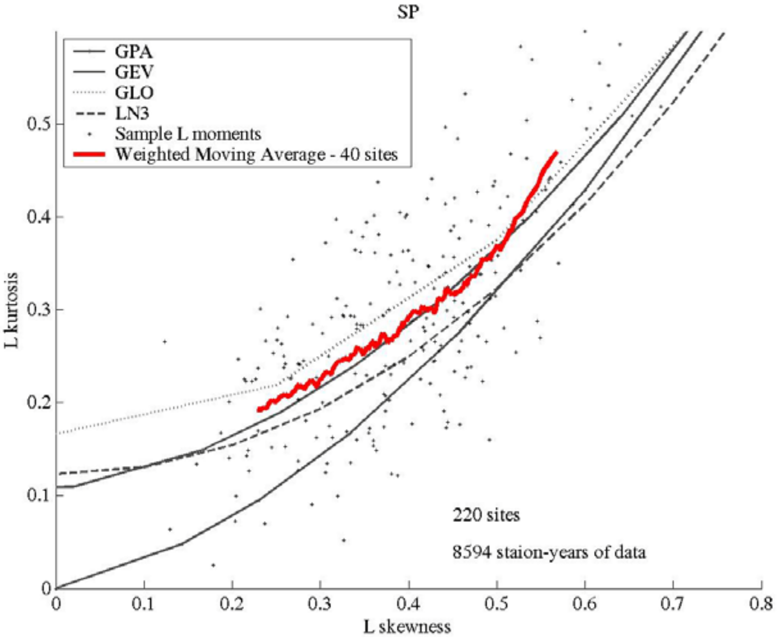

Figure 3.12 L moment ratio diagram for **SPAIN** (SP): sample L moment ratios (dots), together with weighted moving averages (WMA, red lines), weighting sample L moments proportionally to the length of each sample; theoretical relationships between L skewness and L kurtosis for some 3-parameters distributions: Generalized Logistic GLO, Generalized Pareto GPA, 3-parameter Lognormal LN3, and Generalized Extreme-Value GEV.

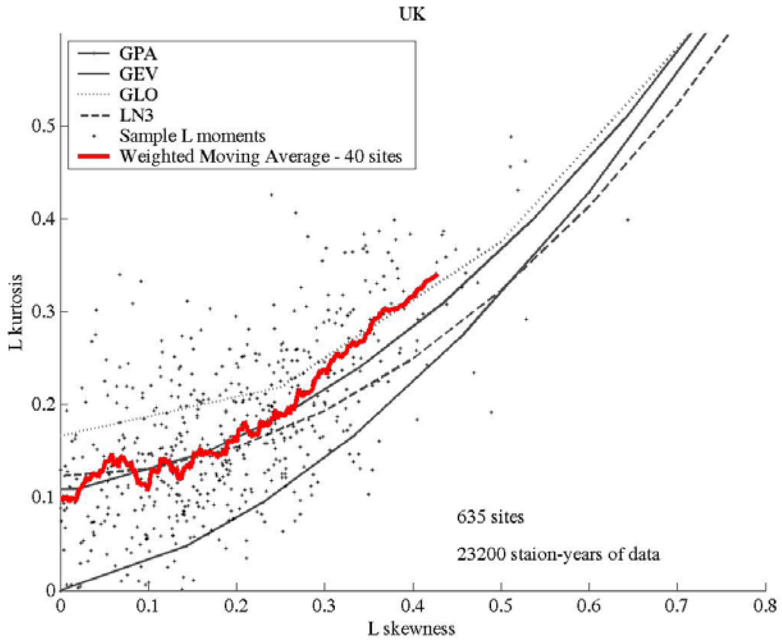

Figure 3.13 L moment ratio diagram for **UNITED KINGDOM** (UK): sample L moment ratios (dots), together with weighted moving averages (WMA, red lines), weighting sample L moments proportionally to the length of each sample; theoretical relationships between L skewness and L kurtosis for some 3-parameters distributions: Generalized Logistic GLO, Generalized Pareto GPA, 3-parameter Lognormal LN3, and Generalized Extreme-Value GEV.

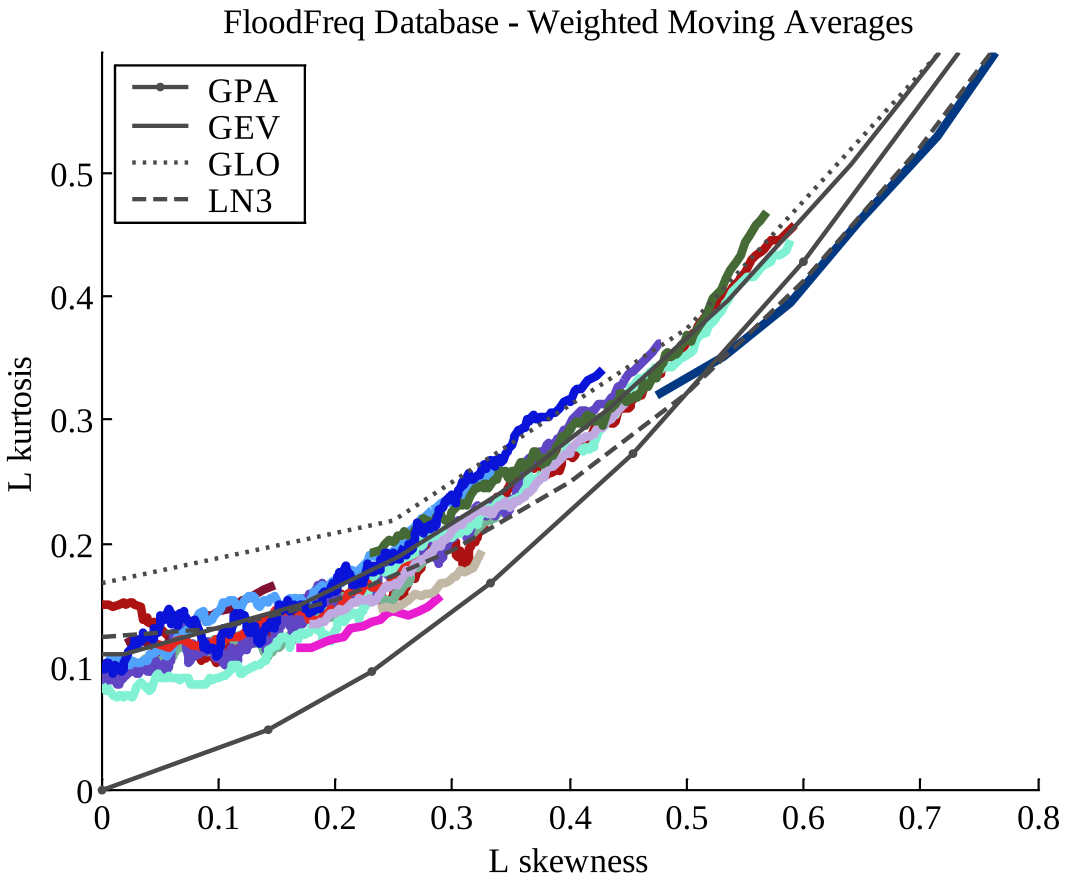

Figure 3.14 L moment ratio diagram for FloodFreq database: national weighted moving averages, weighting sample L moment ratios proportionally to the length of each sample; theoretical relationships between L skewness and L kurtosis for some 3-parameters distributions: Generalized Logistic GLO, Generalized Pareto GPA, 3-parameter Lognormal LN3, and Generalized Extreme-Value GEV.

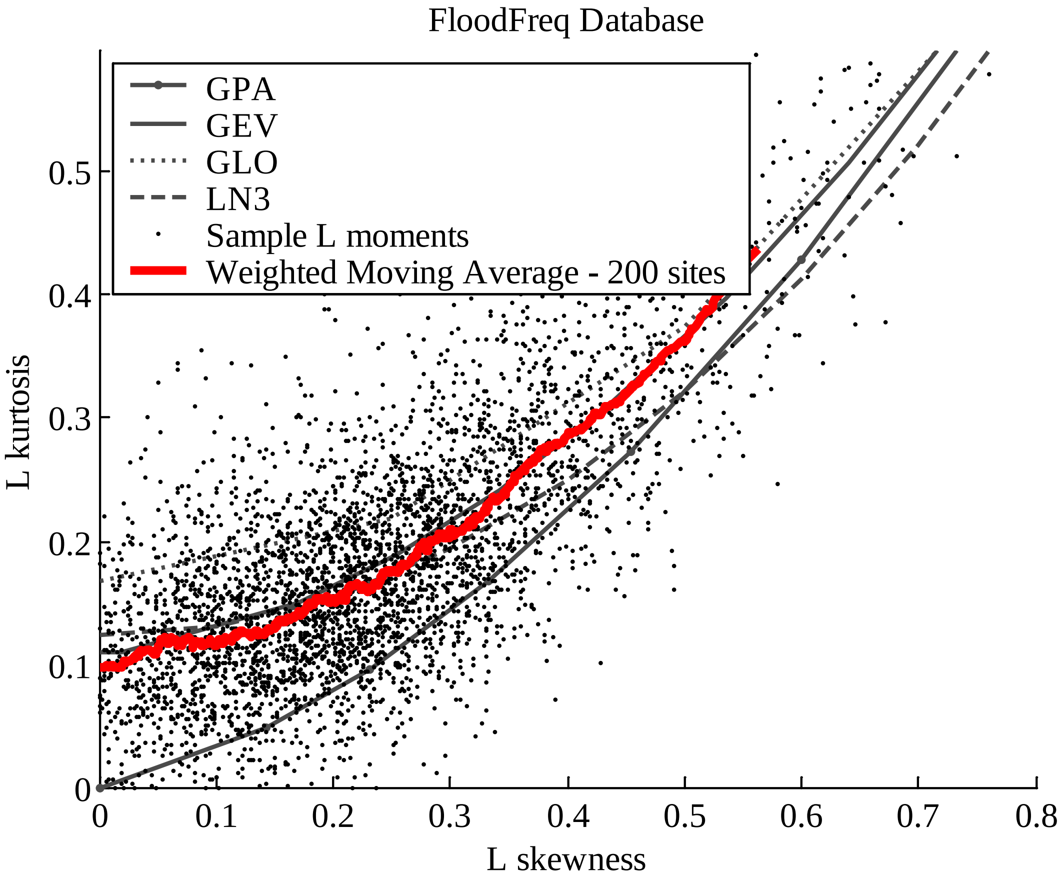

Figure 3.15 L moment ratio diagram for FloodFreq database: sample L moment ratios (dots), together with weighted moving averages (WMA, red lines), weighting sample L moments proportionally to the length of each sample; theoretical relationships between L skewness and L kurtosis for some 3-parameters distributions: Generalized Logistic GLO, Generalized Pareto GPA, 3-parameter Lognormal LN3, and Generalized Extreme-Value GEV.

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WG2 members’ reports

Report Template

The WG2 members' reports are short reviews of existing statistical methods for flood-frequency analysis used or under development in the FloodFreq partner countries.

The partners were asked to focus particularly on regional approaches (delineation of homogeneous pooling-groups of sites, considered catchment descriptors, etc., showing the relationship with any kind of coastal constraints, just in case, particularly with the nearest marine climate conditions), but description of at-site procedures were also accepted.

The structure of each report is presented in the following template, which was circulated among WG2 members:

1 Description of method

1.1 Identification of homogeneous pooling-groups of sites taking into account the vicinity of any sea/lake and their climatic/subsidence conditions

regional scale analysis, delineation of regions, fixed regions vs. region of influence, how regions were delineated etc.

1.2 Estimation of the index flood or site-specific scale factor

for regional scale analysis

1.3 Choice of a frequency distribution

regional and at-site

1.4 Estimation of the frequency distribution

regional and at-site

2 Data

2.1 Catchment descriptors

for regional scale analysis: list of parameters and source, grid size for descriptors retrieved from DEM, grouping method, that is geographical regions, regions of influence, etc. distance to the coast/lake-line; in case of neighbour coast, mean step or length profile

2.2 Flood data

for regional scale and at-site analysis: river name, stream gauge name and location (longitude-latitude-altitude and/or map, water level and speed), record length and time span covered by data, catchment area, hydrological regime, type of series (AMS or PDS), instantaneous peak flows and/or flood volumes, validation and accessibility of the data

3 Discussion

3.1 Purpose and areas of application

design of hydraulic structures, dams, urban hydrology, flood-hazard mapping, etc.

3.2 Merits and drawbacks

applicability to ungauged sites and information required, uncertainty of the estimates, recurrence interval of interest, etc.

3.3 Recommendations for users

4 Case studies

examples of practical applications

5 Plans for future development

6 References

7 Attachments

papers (pdf) published for internal use, open source software (if any)

AT – Austria (HORA Project, Ralf Merz and Jose Luis Salinas)

1. Description of method

The aim of the HORA (HOchwasser Risikoflächen Austria – Flood Risk Areas in Austria) Project was to calculate the flood risk mapping nationwide for the 30, 100 and 200 year flood quantile. The hydrological part of the study obtained the numeric values of these quantiles over the entire 26000 km length of the Austrian river network. The hydraulic simulations used these values in the next stage as boundary conditions in order to calculate the extension of the flood-prone areas for the three return periods.

The methodology used for the at-site statistics was the framework later designed as Flood Frequency Hydrology. The approach, summarized in Merz and Blöschl (2008a), suggests that the statistical methods of flood frequency analysis in the past have placed undue emphasis on solving the estimation problem and that one should make much better use of the wealth of available hydrological knowledge to expand the information beyond the flood sample at the site of interest. This expansion of information can be grouped into three types: temporal, spatial, and causal. Some non-formal, expert judgment-based ways of combining this additional information are presented in Merz and Blöschl (2008b) and shown in Figures AT1 and AT4. In addition, a more formal Bayesian framework has been developed by Viglione et al. (2011) in order to include all sources of available information into the flood estimate.

The Flood Frequency Hydrology philosophy has been used not only in Austria but was also introduced in the latest German guideline for flood estimation, DWA-Merkblatt 552 (2011).

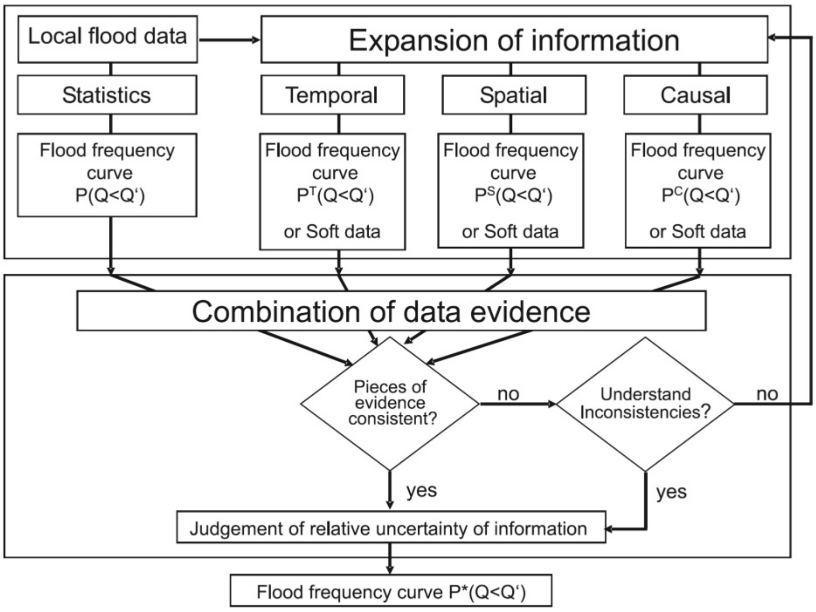


Figure AT1 Schematic of the flood frequency estimation procedure (from Merz and Blöschl 2008b).

Temporal information expansion

Temporal information expansion puts the observed flood sample into the wider context of the hydrological history of the catchment. This is particularly important if the flood records are short, as is often the case in small catchments. The idea of temporal information expansion is that the history gives guidance on the future flood behaviour to be expected. Most importantly, the longer series may help to identify whether the available short record contains decades of untypical low or high flood conditions. The most favorable case, of course, is if a stream gauge with a much longer record is located close to the site of interest. One could correct the flood moments (CV, CS) on the base of the longer series for posterior estimation purposes, if there were extraordinary large floods present in the shorter one that could bias the estimation (see an example in Merz and Blöschl, 2008a). If no long flood records in the region are available, an alternative is to use indices or proxy data that are indirectly related to the flood magnitudes in the past. Historical flood information can date back over centuries and usually provides some evidence of the maximum water level during large floods.

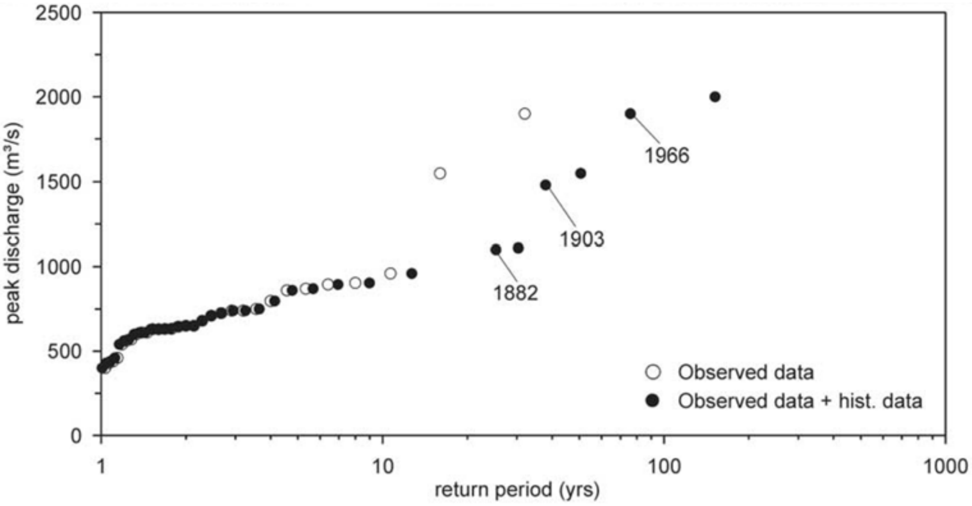


Figure AT2 Flood frequency plot of the Drau at Villach based on observed flood data (open circles) alone and observed and historical flood data (black circles) derived from flood marks and photographs. (From Merz and Blöschl, 2008a).

An example is shown in Figure AT2 for the city of Villach at the Drau River in southern Austria. Runoff has been observed from 1951 to 1981 and there is information about historical floods in 1882 and 1903. The largest flood in the sample was the event of 1966 which, according to the plotting position formula, is associated with a return period of 32 years. If one incorporates historical information, the plotting position can be adjusted to a return period of about 80 years. If one ignores historical flood data the flood frequency curve would overestimates the flood flows at large return periods.

Spatial information expansion

Spatial information expansion is based on using flood information from neighbouring catchments to improve the at-site flood frequency estimation. Additionally, spatial information expansion can be used for estimating flood frequency in ungauged catchments. The underlying assumption of both applications is that space can be substituted for time after suitable transformation. This is the case if the regional trend is indeed representative of the local conditions. Altenmarkt gauge at the upper Enns River is an example of this kind of information expansion. In Figure AT3, the specific 100-year discharges at Altenmarkt and other gauges in the area have been plotted against catchment area. The open circles represent the estimates from the local flood samples alone using the GEV distribution and the method of moments. In addition, regional estimates for the same location have been plotted in the graph that were obtained from the neighboring catchments by top-kriging, without use of the local flood data (pluses). Top-kriging (Skøien et al., 2006) is a geostatistical estimation approach that takes into account river network structure and catchment area. The striking point at Altenmarkt is that the local estimate is much lower than the regional estimate. An analysis of the catchment characteristics such as topography, geology and rainfall did not point to any major differences from the rest of the catchments in the region. However, interviews with the local Hydrographic Service indicated that the stream gauge tends to get inundated during floods and, apparently, the data have not been corrected.

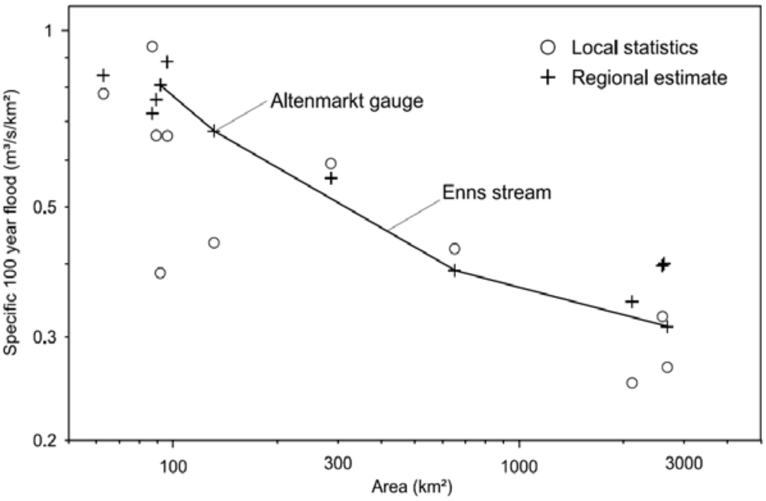
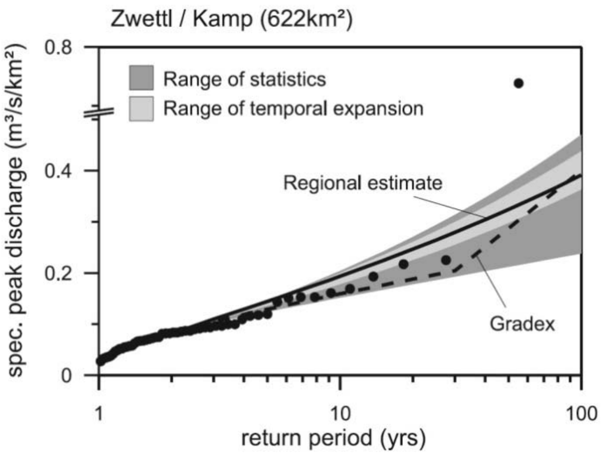


Figure AT3 Discharge-area diagram of the upper Enns valley. Specific 100-year flood discharges derived from locally observed data are shown as open circles. Regional estimates using flood data from neighboring stations are shown as plusses (From Merz and Blöschl, 2008a).

In the example shown here, the 100-year discharges were corrected from 58 m^3/s to 86 m^3/s on the basis of the characteristics of the flood samples in the area, in particular those of the upstream and downstream gauges.

Causal information expansion

The third type of information expansion relates to the use of hydrological understanding of the local flood producing factors to improve the flood frequency estimation at a site. Causal information expansion is particularly important in small catchments, both because fewer and shorter records tend to be available than in larger catchments and because the flood processes are more amenable to analysis than in larger catchments where the regional combination of control can be relatively more important. Flood generation is a highly complex process so, clearly, the flood producing factors will depend on the climatic and the hydrological situation. Obviously, the main control on river floods in most parts of the world is rainfall. The derived flood frequency approach that estimates flood frequencies from rainfall frequencies has attracted considerable interest in the scientific literature but its impact on practical flood estimation has been much more modest. The main problem is that it is difficult to quantify the joint probabilities of the various controls on the flood frequency curve such as rainfall duration, temporal patterns, multiple events, soil moisture and routing characteristics. Simpler, but statistically less rigorous methods have hence enjoyed some popularity. An example is the Gradex method (Guillot, 1972) that assumes that, beyond a threshold return period, any additional rainfall produces a corresponding increase in runoff without losses. The method avoids the joint probability issue to some degree by combining local flood data with the rainfall statistics. While the statistical assumptions may be the subject of some debate, a number of studies have indicated that the method can indeed increase the accuracy of flood estimates at large return periods. Derived flood frequency is particularly appealing if the available rainfall records in the region are much longer than the flood records. In Austria, daily rainfall records, typically, are 100 years while flood records are usually 40 years, and shorter in small basins, so the approach may have some merits.



Type of Information	Data and Method	MAF (m^3/s)	CV	CS	HQ100 (m^3/s)
Statistics	methods of moments, GEV distribution, with or without outlier	57–63	0.51–0.98	1.14–5.21	148–293
Temporal	floods reconstructed from water stages; historical flood information	63	0.7–0.9	4	225–273
Spatial	top-kriging without local data	62	0.81	2.7	243
Causal	Gradex; runoff coefficients	63	0.65–0.85	4–6	215–262
Combination		63	0.8	3.5	248

Figure AT4 (top) Flood frequency plots and (bottom) combination of Data Evidence for the Zwettl Catchment (From Merz and Blöschl, 2008b).

1.1 Identification of homogeneous pooling-groups of sites

In the past, cluster analyses for flood frequency analysis were performed in Austria, according to physiographic and climatic controls. Merz and Blöschl (2005) showed that geostatistical regionalization methods have considerably better performances nationwide, compared with multiple regression, pooling groups or region of influence approaches. Therefore, the method chosen to regionalize the at-site estimates to ungauged catchments was Top-Kriging (Skøien et al., 2006), a geostatistical method that takes into account the river network structure and catchment area, interpolating the 30, 100 and 200-year flood quantiles over the whole Austrian river network length, i.e. 26000 km, 10500 sites (Fig. AT5).

1.3 Choice of a frequency distribution

In previous studies, the performance of several 3 parameter extreme values distributions (GEV, Gen. Pareto, Log-Normal 3, Pearson III, Log-Pearson III, …) were compared and the General Extreme Value (GEV) distribution showed the best results on a national scale.

1.4 Estimation of the frequency distribution

For the at-site estimation of the parameters from the GEV distributions, the method of moments was used, with corrected values of the mean, coefficient of variation, and coefficient of skewness thanks to the temporal, spatial and causal additional information.

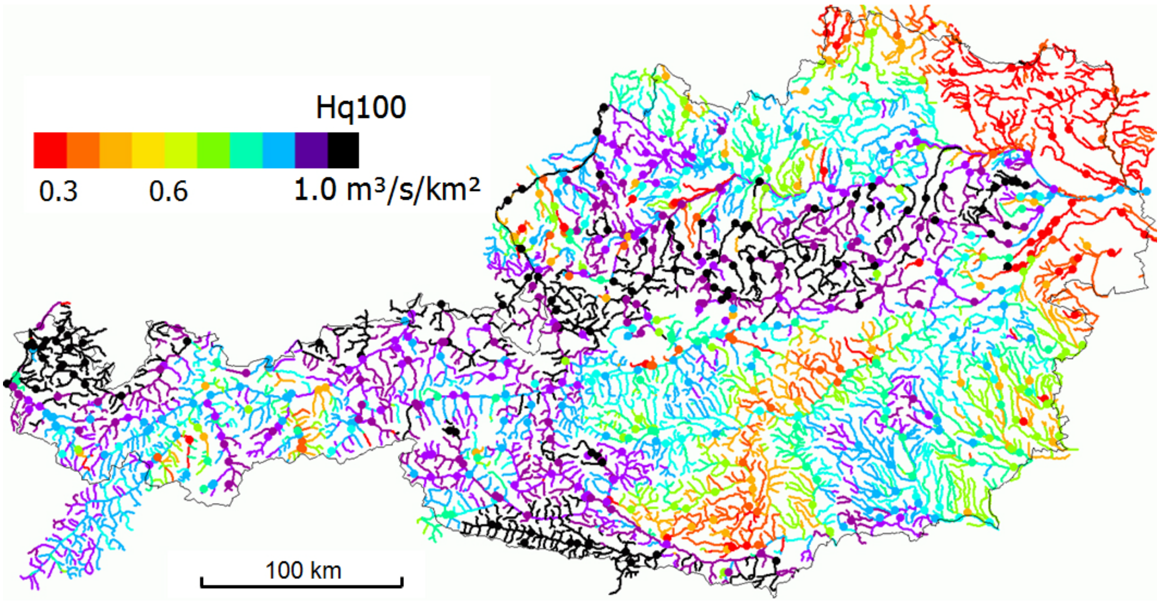


Figure AT5 Regionalisation of the 100-year specific flood quantile over the 26000 km of the Austrian river network with Top-Kriging (points: at-site estimates).

2. Data

2.1 Catchment descriptors

The following catchment descriptors were available for the project

- Location
- Area
- Min, max and average elevation
- Mean annual precipitation
- Geology
- Presence of lakes, reservoirs
- Mean annual temperature

2.2 Flood data

For the at-site estimates, runoff data from 938 gauging stations with varying resolution and coverage was available, from around 100 years in the historical gauges (e.g. in the Danube or the Inn) to an average of 30-40 record length. 715 of the stations have hourly resolution since the mid 70's, the rest are annual maxima extracted from mean daily flows.

3. Discussion

3.1 Purpose and areas of application

The main outcomes of the HORA projects were, i) the at-site flood frequency distributions of most of the Austrian stations and the interpolated values for specific quantiles over the whole river network, and ii) a detailed cartography of the flood-prone areas given by the hydraulic simulations for the 3 return periods (30, 100 and 200 years) available in an online application (www.hochwasserrisiko.at).

5. Plans for future development

The Austrian Federal Ministry of Environment is currently developing a project to update the HORA values including in the hydrologic analyses the flood data of the last years and improving the hydraulic simulations with a more detailed DEM.

6. References

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BE – Belgium (Patrick Willems)

1. Description of method

1.1 Identification of homogeneous pooling-groups of sites

The Flanders region of Belgium has been split into three homogenous regions (see Figure BE1). The identification of these regions is based on two river flow properties: the specific discharge (river flow per unit river basin area) and the coefficient of variation (CV), using the principal component analysis.

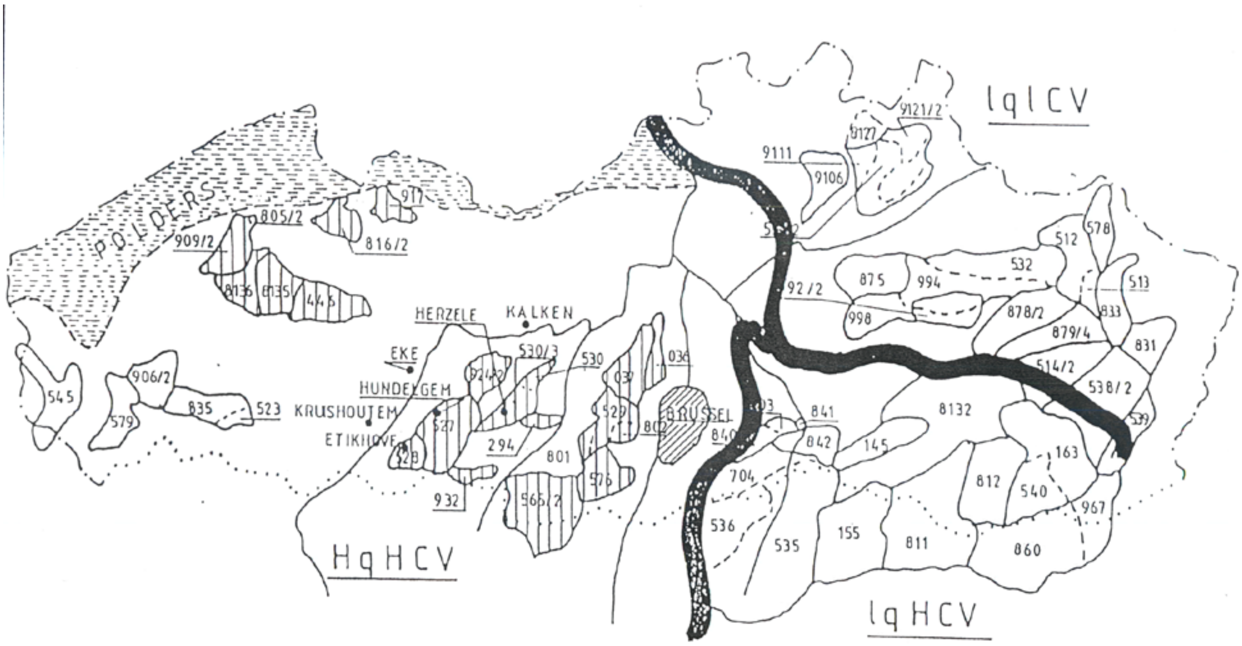

Figure BE1: Three homogenous regions identified for the Flanders (Northern) region of Belgium: HqHCV (high specific discharge and high CV), lqlCV (low specific discharge and low CV), lqHCV (low specific discharge and high CV).

1.2 Estimation of the index flood or site-specific scale factor

Only the area of the catchment has been considered to scale the river flow (use of the specific discharge).

1.3 Choice of a frequency distribution

At-site and regional flood frequency distributions are based on the extreme value theory: use of the Generalized Pareto Distribution (GPA) calibrated to “nearly independent” extremes extracted from river flow series. These extremes can be seen as a Partial Duration Series (PDS) and are extracted from the series using hydrologic independence criteria. The criteria are based on the inter-event time, the inter-event low flow discharge and the peak height. The method is explained in Willems (2009).

1.4 Estimation of the frequency distribution

The GPA distribution is calibrated using a method based on weighted linear regression in quantile plots (Willems et al., 2007).

2. Data

Data (catchment descriptors and flood data) from more than 100 stations were used. Nevertheless, most data are not all publicly available; they are owned by the Hydrologic Information Centre (HIC) of the Authorities of Flanders or the Flemish Environment Agency.

3. Discussion

3.1 Purpose and areas of application

See WP3: Flood probability and flood risk mapping, design of hydraulic structures, impact of urban drainage, …

3.2 Main features, merits and drawbacks

Merits:

- Only one extreme value distribution has to be considered: the GPD.
- Effect of river flooding on the tail of the extreme value distribution is taken into account.

Drawbacks:

- Following the extreme value theory, the GPD only holds perfectly when considered asymptotically in the tail (towards values of +∞). This means that they may not hold exactly for the lower extremes extracted from river flow series. In most practical applications, however, it has been seen that the GPD fits well, also for lower values.

4. Case studies

Examples of practical applications

- River flow extremes (Willems et al., 2007)
- Rainfall extremes (Willems, 2000)
- Storm surge levels along the Belgian coast at Ostend (Willems and Verwaest, 2008)

5. Plans for future development

Demonstration of the flood thresholds by combined use of extreme value analysis in quantile plots and river hydrodynamic models.

6. References

Beirlant, J., Teugels, J.L., Vynckier, P. (1996): *Practical analysis of extreme values.* Leuven University Press, Leuven.

Guillou, A., Willems, P. (2006): Application de la théorie des valeurs extrêmes en hydrologie. *Revue de Statistique Appliquée*, 56 (2), 5–31.

Hill, B.M. (1975): A simple and general approach to inference about the tail of a distribution. *Ann. Statist.*, 3, 1163–1174.

Lang, M., Ouarda, T.B.M.J., Bobée, B. (1999): Towards operational guidelines for over-threshold modelling. *Journal of Hydrology*, 225, 103–117.

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Willems, P. (2009): A time series tool to support the multi-criteria performance evaluation of rainfall-runoff models. *Environmental Modelling & Software*, 24(3), 311–321.

Willems, P., Guillou, A., Beirlant, J. (2007): Bias correction in hydrologic GPD based extreme value analysis by means of a slowly varying function. *Journal of Hydrology*, 338, 221–236.

Willems, P., Verwaest, T. (2008): Extreme value analysis of coastal levels, with and without convolution of astronomic and storm surge components. *Coastal Engineering*, 5, 4099–4108.

BG – Bulgaria (Neyko M. Neykov)

1. Description of method

1.1 Identification of homogeneous pooling-groups of sites

The cornerstone in Regional Frequency Analysis (RFA) is the assumption that the data come from homogeneous regions. Usually the process of formation of homogeneous regions is based on the at site characteristics using objective (clustering) and subjective techniques. Once a region of sites is formed it is subsequently evaluated by the measure of regional heterogeneity *H*, developed by Hosking and Wallis (1987). A region is defined as "definitely heterogeneous" if *H* > 2. The H statistics, however, do not tell us anything about those sites responsible for the heterogeneity. Thus if regions of sites are identified as heterogeneous some redefinition of these regions must be made. For screening of the data Hosking and Wallis (1987) recommend the usage of the discordancy measure D_i^2 which identifies unusual sites that are grossly discordant with the group as a whole. The discordancy is measured in terms of the sample L-moment ratios (L-CV, L-skewness, L-kurtosis) of the site's data and is computed for each site. If the data for the region is represented by the 3-dimensional vectors $u_i = (t^{(i)}, t_3^{(i)}, t_4^{(i)}),\ i = 1, \cdots, N$ then the discordancy measure for site *i* is defined as

$$D_i^2 = (u_i - \bar{u})^t S^{-1} (u_i - \bar{u})^t,$$

where $\bar{u} = \dfrac{1}{N}\sum_{i=1}^{N} u_i$ and $S = \dfrac{1}{N-1}\sum_{i=1}^{N} (u_i - \bar{u})(u_i - \bar{u})^t$ are the sample mean and covariance matrix of the region. This discordancy measure test is equivalent to the classical approach for identifying outliers in multivariate data based on a distance calculated from each data point to a center of the data which usually is called Mahalanobis distance, see Johnson and Wicheren (1992). The classical estimates of the mean and dispersion are extremely sensitive to discordant observations and even a couple of such observations could attract the mean and inflate the variance in their direction thus preventing the method from discovering them, since they will not necessarily get large values of their discordancy measures D_i^2. To overcome this deficiency of the classical method we need robust estimates of the multivariate location and covariance matrix to plug them in the formula of the discordancy measure instead of the classical ones. The new robust discordancy measure is defined as

$$RD_i^2 = (u_i - T)^t C^{-1} (u_i - T)^t,$$

where *T* and *C* are some robust estimates of the mean and the covariance matrix of the region.

The usage of the Minimum Covariance Determinant (MCD) estimates of *T* and *C* is recommended by Neykov et al. (2007). The performance of the classical discordancy measures D_i^2 and RD_i^2 with respect to their ability to detect discordant sites were investigated by a Monte Carlo simulation study in a range of RFA framework situations. As a whole the study shows that robust discordancy measure based on MCD not only outperform the classical one but is also consistent with the *H* statistic. Furthermore, the necessary algorithm for computing the robust discordancy values is readily available in R for instance the package *rrcov* developed by Todorov (2006) and the application of this algorithm for the purposes of RFA is straightforward. Thus we recommend its use in the RFA framework as a tool for detection of discordant sites.

6. References

Hosking, J.R.M. and Wallis, J. R. (1997): *Regional Frequency Analysis: An Approach Based on L-moments*. Cambridge University Press.

Neykov,N., Neytchev, P.N., Van Gelder, P.H.A.J.M. and Todorov, V.K. (2007): Robust detection of discordant sites in regional frequency analysis. *Water Resour. Res.*, 43, W06417, doi:10.1029/2006WR005322.

CY – Cyprus (Antonis Toumazis)

1. Description of method

The most widely used method for flood flow and frequency prediction in Cyprus is via the storm analysis (indirect approach, frequency analysis of rainfall events coupled with a suitable rainfall runoff model). This is mainly a consequence of: the lack long records of streamflow data, the small number of perennial streams, and the small size of the island (see Figure CY1). The island of Cyprus, with an area of 9.251 km^2, experiences severe water shortage problems. In order to address these problems the slogan “Not a drop of water to be wasted to the sea” was adopted in the early 1960s. As a consequence, a series of dams has been constructed over the years. Today almost all (seasonal) rivers are dammed (Figure CY1) and Cyprus has the largest number of dams per area in Europe.

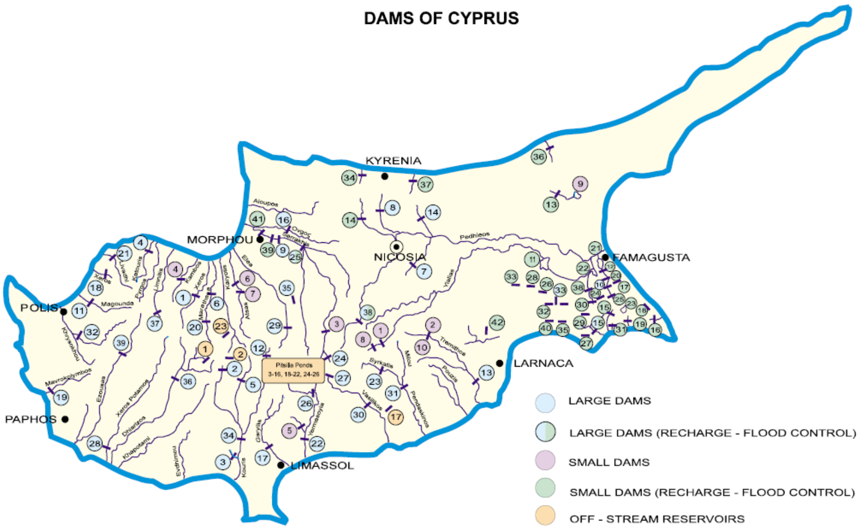

Figure CY1 The dams of Cyprus.

Flood frequency analysis is used in the design of dams, the design of (dry) river crossings (bridges and culverts) and storm water drainage systems. The methods used for flood frequency analysis for these cases are:

- Reservoir / dam design (of significant rivers): Extreme Value Analysis of gauged rivers and storm analysis
- River crossings (bridges and culverts): Mainly storm analysis (extreme value analysis if available data)
- Storm Water Drainage systems: Storm Analysis

1.1 Identification of homogeneous pooling-groups of sites

Due to the small size of Cyprus the whole country is considered as one region.

1.2 Estimation of the index flood or site-specific scale factor

Flood estimation using storm analysis is based on site-specific rainfall estimation. A most comprehensive study was published recently (Pashiardis, 2009) which derived rainfall intensity – duration – frequency distribution/ curves. The equations describing these curves are in the format:

$$i(d,T)=\frac{\lambda\psi+\frac{\lambda}{k}\left[\left(-\ln\left(1-\frac{1}{T}\right)\right)^{-k}-1\right]}{(d+\theta)^{\eta}}$$

where
i : the rainfall intensity (mm/hour)
T : the return period (in years)
d : rainfall duration (hour)
k, λ, ψ, η, θ are constants for the different locations.

1.3 Choice of a frequency distribution

A recent study (Galiouna 2011) investigated the empirical relationships for the estimation of peak flood flows in Cyprus. This study analysed the peak annual flows in 34 streams (Figure CY2) with measurement of at least 20 years and no dam upstream.

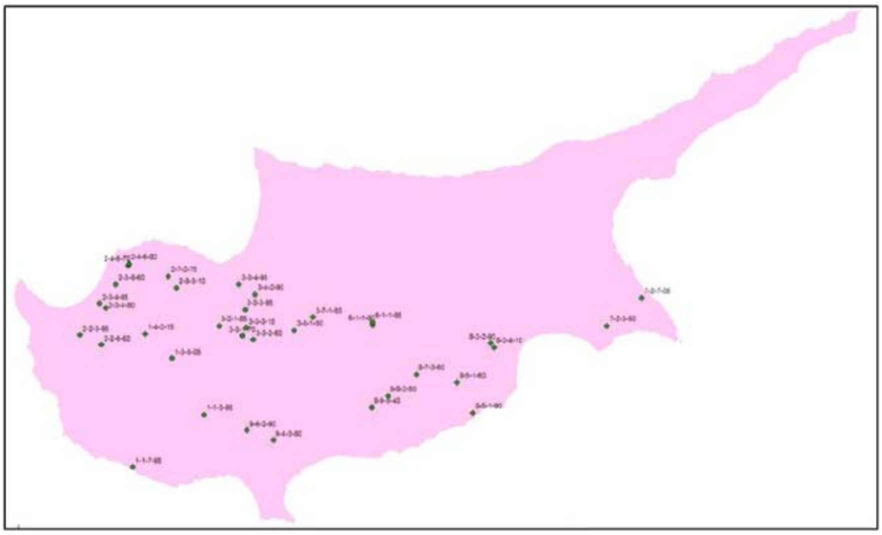

Figure CY2 Locations of data analysis.

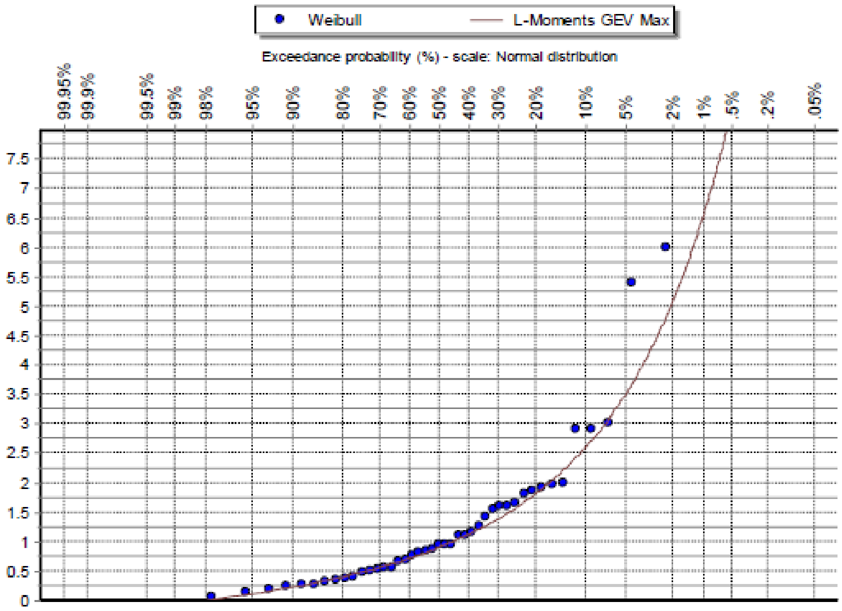

Figure CY3 Example of analysis.

The conclusion from this analysis is that the GEV distribution combined with the method of Lomoments is suitable for small flows and high probability events (see Figure CY3). For extreme flow, low probability events, the above method is not at all suitable and it can even prove dangerous as it under-predicts the extreme flows.

2. Data

The Water Development Department, Ministry of Communications and Works of the Republic of Cyprus, publishes yearly books with data of stream flows at selected gauge stations. The data at each gauge include the river/ stream name, the station location (x, y co-ordinates and elevation), the area of the catchment area, the mean annual precipitation, the mean annual runoff, the time of concentration, the mean basin slope and the mean river slope, instantaneous peak flow.

3. Discussion

The analysis carried out on peak flood flows failed to predict the extreme flows for low probabilities might be due to the particular climate of the island which experiences long drought periods. The reliability of these methods might improve when data of longer duration become available.

4. Case studies

There are numerous practical applications of flood frequency analysis for the designs of dams, bridges, culverts, storm drainage systems. The use of regional analysis has not been used yet.

5. Plans for future development

Analysis of data of longer time series, correlation with rainfall data prior to the peak flow measurement and area characteristics are future long term plans.

6. References

Galiouna, E. (2011): *Investigation of empirical relationships for the estimation of peak flood flows in Cyprus*. MSc Dissertation, National Technical University of Athens.

Pashiardis, S. (2009): *Compilation of rainfall curves in Cyprus*. Meteorological Note no. 15, Meteorological Service, Ministry of Agriculture, Natural Resources and Environment, Nicosia.

DE – Germany (Bruno Merz)

Several methods of flood frequency analysis (FFA) are available for different federal states of Germany. Two of these methods are described in more detail below.

German method #1:
FFA for the federal states of Bavaria, Hesse and Schleswig-Holstein

1. Description of method

1.1 Identification of homogeneous pooling-groups of sites

Homogeneous pooling-groups have been derived by means of cluster analyses. As a measure for homogeneity the H1 statistic according to Viglione et al. (2007) has been applied.

1.2 Estimation of the index flood or site-specific scale factor

The well established index flood procedure has been extended in terms of index flood regionalisation and the identification of homogeneous regions. As a first step, checks have been made as to whether all stream gauges of the federal state exhibit a similar seasonal pattern using the seasonality index suggested by FEH (1999). The regionalisation of the index flood has been carried out, for each federal state separately, by deriving a multiple regression model in which the mean annual peak flow (*MHQ*) is a function of several catchments descriptors (see Section 2). Which of the catchment descriptors are included in the corresponding regression model varies from federal state to federal state. In all regression models *MHQ* is logarithmically transformed. Some of the catchment descriptors have no transformation, some are logarithmically transformed and some show a square root transformation. Again, which transformation has become significant for the single catchment descriptor varies for the regression models of the different federal states.

1.3 Choice of a frequency distribution

Generalized extreme value (GEV) distribution

1.4 Estimation of the frequency distribution

By means of regional L-moments

2. Data

2.1 Catchment descriptors

- Parameters: catchment area, cumulative channel-segment lengths, normalised sum of channel lengths, FARL-index, percentage area of different land use classes, available water capacity, vertical permeability, CN value, river regimes, depth to ground-water table, mean elevation, median elevation, standard deviation of the elevations, topographical index, slope, mean annual precipitation, maximum daily precipitation, catchment torrential rain.
- Data sources: digital elevation model (grid length: 50 m), stream network, lakes, land cover, river regimes, geology, hydrogeology, soils, depth to ground-water table, precipitation records.
- Grouping method: topological aggregation.

2.2 Flood data

- Stream gauge name and location: for Bavaria: N/A, for Hesse: 113 stream gauges and for Schleswig-Holstein: 160 stream gauges.
- Record length and time span covered by data: different time spans.
- Catchment area: some km² to several thousand km².
- Type of series (AMS or PDS): AMS.
- Instantaneous peak flows and/or flood volumes: flood peaks of different return periods.
- Validation of the data: N/A.
- Accessibility of the data: N/A.

3. Discussion

3.1 Purpose and areas of application

For technical flood protection solutions and the general knowledge of runoff characteristics

3.2 Main features, merits and drawbacks

- Recurrence interval of interest: any.
- Applicability to ungauged sites: yes.
- Uncertainty of the estimates: Information about the errors is published.

3.3 Recommendations for users

For Hesse: Applying the method for catchments smaller than 15 km² is not recommended.

4. Case studies

Application to the sites of the official areal water system register (hydrologische Flaechenverzeichnisse) of Bavaria, Hesse, Bavarian Regnitz area and Schleswig-Holstein.

6. References

Brahmer, G. (2008): Regionalisierung von Hochwasserkennwerten für Hessen. *Jahresbericht 2008 des HLUG*.

Institute of Hydrology (1999): *Flood Estimation Handbook* (FEH). Wallingford, UK.

Viglione, A., Laio, F., Claps, P. (2007): A comparison of homogeneity tests for regional frequency analysis, *Water Resources Research*, 43, W03428, doi:10.1029/2006WR005095.

Willems, W. (2008): Statistische Hochwasserregionalisierung mittels erweiterter Index-Flood-Prozedur. *Wasserwirtschaft* 11, 35–40.

German method #2:
FFA for the federal state of Baden-Wuerttemberg

1. Description of method

1.1 Identification of homogeneous pooling-groups of sites

No homogeneous pooling-groups

1.2 Estimation of the index flood or site-specific scale factor

The regionalisation concept for the flood, mean or low flow parameters bases on a multiple, linear regression approach:

$$\ln Y = C_0 + C_1 \ln P_1 + C_2 \ln(P_2 + 1) + C_3 \ln(P_3 + 1) + C_4 \ln P_4 + \cdots + C_8 \ln P_8 ,$$

where *Y* is the relevant flood, mean or low flow parameter. The values P_1 to P_8 represent the catchment descriptors which are listed in Section 2.

For peak flows of return periods between 2 and 100 years:

1) In order to calculate the site-specific mean annual specific peak flow *MHq*: *Y* = *MHq*.
2) In order to calculate the site-specific specific peak flow of a certain return period *Hq* in relation to *MHq*: *Y* = *Hq*/*MHq*, with *MHq* from step 1.

In a study called KLIWA a method has been developed to fix “climate factors“ against different return periods and different “climate regions” of Baden-Wuerttemberg. By allocating a catchment to such a “climate region” it is now possible to get values for the climate factors for floods of different return periods.

1.3 Choice of a frequency distribution

At-site choice of the“optimal” frequency distribution according to Deutscher Verband fuer Wasserwirtschaft und Kulturbau e. V. (1999).

1.4 Estimation of the frequency distribution

See Section 1.3.

2. Data

2.1 Catchment descriptors

- Parameters: catchment area, percentage of urban area, percentage of forest area, weighted slope, channel-segment lengths, characteristic channel-segment lengths, average annual rainfall and a so-called landscape factor which is a function of hydrogeological units (Hydrogeologische Einheiten) and local peculiarities.
- Data sources: digital elevation model (sink filled, grid length: 50 m) & grid based on the Landsat-TM survey of the year 1993 (land use for 16 categories) & a grid for the average annual rainfall (1931–1994) produced in 1995/1996 (grid length of 1000 m).
- Grouping method: lumped parameters.

2.2 Flood data

- Stream gauge name and location: more than 300 stream gauges of Baden-Wuerttemberg.
- Record length and time span covered by data: different time spans.
- Catchment area: some km² to several thousand km².

- Type of series (AMS or PDS): AMS.
- Instantaneous peak flows and/or flood volumes: flood peaks of different return periods (HQ_2–HQ_{100}), factors to estimate extreme flood peaks (f_{200}–$f_{10\,000}$), climate factors ($f_{K,2}$–$f_{K,1000}$) to consider predicted climate changes, mean flow (MQ) and low flow values of different return periods (MNQ, NQ_2–NQ_{100}), mean low flow durations (ND_2–ND_{100}).
- Validation of the data: AMS series are constantly validated by the Landesanstalt fuer Umwelt, Messungen und Naturschutz Baden-Wuerttemberg.
- Accessibility of the data: plotting positions derived by using the AMS series have been provided on a CD.

3. Discussion

3.1 Purpose and areas of application

To design water engineering structures and to evaluate the flood risk along natural watercourses and to allow sustainable design of flood-protection measures including strategies for their operation for present as well as for future climatic conditions

3.2 Main features, merits and drawbacks

- Recurrence interval of interest: 2 to 100 and 200 to 10000.
- Applicability to ungauged sites: yes.
- Uncertainty of the estimates: Information about the errors is published.

4. Case studies

Application to the sites of the official areal water system register (Gewaesserkundliches Flaechenverzeichnis/GKFV) of Baden-Wuerttemberg.

6. References

Deutscher Verband fuer Wasserwirtschaft und Kulturbau e. V. (1999): *Statische Analysen von Hochwasserabfluessen*. DVWK-Merkblaetter zur Wasserwirtschaft; Heft. 251, Wirt-schafts- und Verl.-Ges. Gas und Wasser, Bonn.

Ihringer, J., Becker, R., Brunner, R., Harlos, S., Kiefer, H., Merz, R., Neff, H.-P., Luft, G., Marusic, D., Hoenig, U. and Casper, M. (1999): *Hochwasserabfluss-Wahrscheinlichkeiten in Baden-Wuerttemberg*. Landesanstalt fuer Umweltschutz Baden-Wuerttemberg, Oberirdische Gewaesser/Gewaesseroekologie, 54.

Neef, P. and Ihringer, J. (2002): Regionalisation model for flood events in Baden-Wuerttemberg based on a multiple linear regression model. In: *M. Spreafico and R. Weingartner (Editors), International Conference on Flood Estimat*ion. CHR Report. CHR/KHR, Bern/ Schweiz, 601-610.

Ihringer, J., Becker, R., Blatter, A., Neff, H.-P., Preuss, P., Luft, G., Straub, H., Vormann, E. and Beerling, P. (2004): *Mittlere Abfluesse und mittlere Niedrigwasserabfluesse in Baden-Wuerttemberg*. Landesanstalt fuer Umweltschutz Baden-Wuerttemberg, Oberirdische Gewaesser/Gewaesseroeokologie, 86, CD-ROM.

Ihringer, J., Becker, R., Blatter, A., Liebert, J., Preuss, P., Luft, G. and Straub, H. (2005): *Abflusskennwerte in Baden-Wuerttemberg, T. 1: Hochwasserabfluesse, Landesanstalt fuer Umweltschutz Baden-Wuerttemberg*. Oberirdische Gewaesser/Gewaesseroekologie, 94, CD-ROM.

Blatter, A. S., J. Liebert, P. A. Preuss, J. Szabadics and Ihringer, J. (2007): Information System “BW_Abfluss“: Regionalisation of flood, mean and low flow parameters. *Advances in Geosciences*, 11, 57-61.

FI – Finland (Nora Veijalainen)

1 Description of method

1.1 Identification of homogeneous pooling-groups of sites

Regional flood frequency analysis has not been performed in Finland and therefore no pooling areas have been identified. If there are no observations for at least 20 years on the site where hydrological design values are needed, observations from nearby stations in the same watershed, observations from reference watersheds with similar hydrological conditions, values based on nomograms using hydrological properties and climatology or calculations based on hydrological model data are used to estimate the design values (Ministry of Forestry and Agriculture, 1997)

1.2 Estimation of the index flood or site-specific scale factor

No special scale factor is calculated.

1.3 Choice of a frequency distribution

The traditionally used and officially recommended flood distribution in Finland is the Gumbel distribution. The dam safety code of practice by Ministry of Forestry and Agriculture (1997) defines that the Gumbel distribution should be used for at-site flood frequency analysis on unregulated sites with more than 20 years of discharge observations. Other distributions such as log-Pearson type 3, Pearson type 3, lognormal and gamma distribution have been tested in case studies at-site locations, but large-scale studies with other distribution have not been carried out.

1.4 Estimation of the frequency distribution

Flood frequency analysis is performed using the Gumbel distribution with annual maximum series of at-site observations when available. Environmental administration use the program Hydvalikko developed at Finnish Environment Institute to fit the Gumbel distribution to the at-site observed series. The database of this program includes most of the discharge series available in Finland and includes the same data as in the national data archive. Method of moments is used to estimate parameters of the Gumbel distribution.

For ungauged sites observations close by in the same watershed or from reference watersheds with similar hydrological conditions are used if these are available. If appropriate reference watersheds do not exist, nomograms and hydrological properties of the runoff are used in planning. Nomograms relating to e.g. the basin area, maximum snow water equivalent, average slope, percentage of lakes and field to the magnitude of average maximum spring runoff have been published (e.g. Kaitera, 1949, Kuusisto, 1985). Simulated discharges from the hydrological model in Finland, The Watershed Simulation and Forecasting System (WSFS), covering almost the entire country, can be used for ungauged basins after quality checks.

2. Data

2.1 Catchment descriptors

The national data archive Hertta/Oiva, (www.ymparisto.fi/oiva) includes daily discharge and water-level data with some basic catchment desriptions. The description in this database include basin area, lake percentage, coordinates of the measurement site, first and last date of observations, rating curces etc. The entire country has been divided into subcatchments, approximately 6,000, for which subcatchment area, lake percentage, entire basin area and lake percentage are available. Other sections available in this data archive include data on lakes, such as size, location and, when available, the water level-area-volume curve and infromation on hydrological structures and modifications including data on dams, regulation rules etc.

2.2 Flood data

Discharge and water-level data are collected for a national database run by the Finnish Environment Institute (SYKE). This database is available for the government institutes and a version in Finnish is also available for the general public at www.ymparisto.fi/oiva after registration. Data are produced by SYKE, regional authorities, water power producers etc. The database contains daily data from 620 discharge observation points and 370 discharge stations are currently observed. Discharge observations for 30 years or more are available for approximately 200 stations. The longest record commenced in 1863, while several series have more than 90 years of data available. The observations are stored in the database as daily mean discharges. Annual maximum series is used flood studies, usually with the calendar year, but somethimes with the hydrological year (Sept-Aug).

Discharge data is determined by the rating curve method using the continuous daily water-level data or by the hydropower plants. Rating curve extrapolation causes uncertainties in the largest discharge values. National guidelines and international ISO standards are used as guidelines in the determination the discharge. Quality checks and reduction for ice impact have been conducted for the data in the national database.

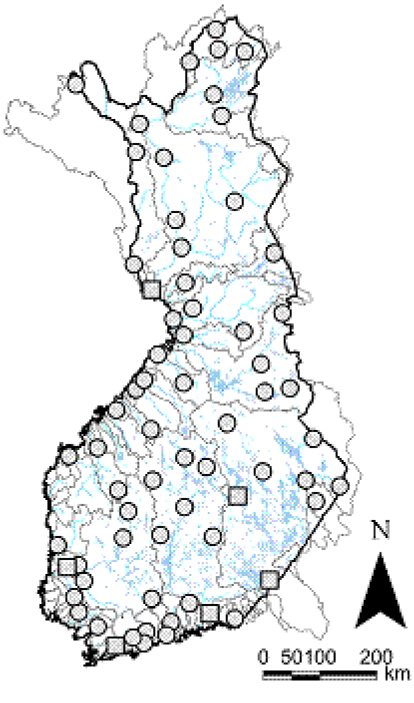

Figure FI1: Map of gauging station locations submitted to COST Action ES0901. Circles are unregulated sites. Squares are sites that are markedly affected by regulation.

Subset of 67 discharge observation stations was selected as an example dataset for COST Action ES0901. This dataset covers different regions and different types of catchments in Finland (Figure FI1). All these stations have long and good-quality observation records; the stations are relatively independent of one another, although some stations are located within the catchment area of other stations in larger catchments. Most of the stations are not affected by regulation, but in order to maintain the representativeness of the stations and include the most important flood risk areas, some stations moderately affected by regulation were also included. This subset of discharge observation stations has been used in previous studies (Veijalainen et al., 2010)

3. Discussion

3.1 Purpose and areas of application

The main areas of application for flood frequency analysis in Finland are flood hazard and risk mapping, design of structures and dams and building codes for lowest construction heights.

3.2 Main features, merits and drawbacks

The main focus of interest in Finland is floods with return period of 20-250 years.

Lack of regionalization methods is a drawback in Finland, but flood estimates for ungauged basins are not often needed in Finland. This is due to the relatively dense and good quality observation network and sparse population intensity, which leads to fewer potential flood areas. At-site observations or at least observations nearby are available for all the major flood areas in Finland.

6. References

Kaitera, P. (1949): On the melting of snow in springtime and its influence on the discharge maximum in streams and rivers in Finland. Teknillisen korkeakoulun tutkimuksia 1. Helsinki.

Korhonen, J. and Kuusisto, E. (2010): Lon- term changes in the discharge regime in Finland. *Hydrol. Res.*, 41 (3-4), 253−268.

Kuusisto, E. (1985): Estimation of mean maximum spring runoff in Finland. *Aqua Fennica*, 15, 154, 47−51.

Ministry of Agriculture and Forestry (1997): Patoturvallisuusohjeet. [Dam safety code of practice] [In Finnish, abstract in English] Maa- ja metsätalousministeriön julkaisuja 7/1997. Helsinki. 90 pp.

FR – France (Michel Lang)

1. Description of method

Numerous studies are based on the extreme value theory, by fitting a Generalized Extreme Value, resp. Generalized Pareto distribution, to annual maximum floods, resp. peak-over threshold values. As sampling and model uncertainty remain very large when fitting a distribution from a data series of 20-30 years to assess rare flood (return period greater than 100 years), it is recommended that the extrapolation of EVT distributions be limited. Such an approach remains valid for large basins with long data series (at least 50 years of record), or for basins where historical data is available. In France, Miquel (1984) presented a flood guideline based on a Bayesian approach. Prior information on flood distribution is based on EVT distributions taken from local data series. The Bayes formula is then applied to assess the posterior distributions by adding a set of historical floods. Specific studies on the reconstruction of discharge values for historical floods have been undertaken in the context of several research projects (see Table FR1).

Table FR1 Studies including historical data in the flood frequency analysis.

Basin	Stations	Systematic records	Historical Period (largest floods)	Research Project
Guiers	St Laurent du Pont	1970-1998	1733-1969	Historisque-Guiers
Isère	Grenoble	1968-1998	1601-1967	D. Cœur PhD thesis (Univ. Grenoble II) and Historisque-Isère
Ardèche	Vallon and St Martin	1980-2001	1644-1979	R. Naulet PhD thesis (Cemagref-INRS), Historisque-Ardèche, SPHERE project
Gard	Alès Anduze Mialet St Jean	1893-1980 1892-2005 1892-2005 1892-2005	1604-1891 1741-1891 1741-1891 1841-1891	InondHis project
Hérault	Ganges Gignac	1970-2005 1989-2005	1795-1969 1812-1988	
BVAude	Orbiel Clamoux Saltz Lauquet	1968-2002 1964-1991 1968-2003 1968-1996	1788-1967 1844-1963 1820-1967 1820-1967	O. Payrastre PhD thesis (Cereve), InondHis project

These long series, contrary to those resulting from the HYDRO bank (see section 2.2), are not continuous: they contain only the values of the largest known floods. However, they yield some very interesting information on the predictive estimation of floods, judging by the exceptional character of the strong values of discharge. Naulet *et al.* (2005) presented a comparison between GEV distributions on the Ardeche basin, fitted by systematic records only (1980-2001) and by systematic records and historical data (1980-2001 + 1645-1979), the latter being larger. Lang *et al.* (2010) and Neppel *et al.* (2010) presented a Bayesian framework accounting for random errors related to water-level readings, and systematic errors related to over-under estimation of the rating curve. It is shown on the Gard basin that ignoring the rating curve errors may lead to an unduly optimistic reduction in estimation of flood discharge quantiles.

At-site statistical methods for derived flood frequency analysis

i) Gradex method

The Gradex method (Guillot and Duband, 1967; CFGB, 1994) is a rainfall-runoff probability approach to computing extreme flood discharges, with a recurrence interval between 100 and 10,000 years. The principle of the method is to find the asymptotic behaviour of the probability model for rare flood volumes from a probability model for cumulative extreme rainfalls. The first step is to set the unit time for all rainfall and flood events, and to adopt a duration *d* corresponding to the average base time of the direct runoff hydrographs. The method is based on three assumptions:

1) The asymptotic distribution for annual maximum rainfalls is a Gumbel distribution, which scale parameter is called the gradex $a_p(d)$. The rainfall distribution is assessed by the product of the distributions functions of seasonal maximum rainfalls. The gradex of annual maxima approaches the largest seasonal gradex asymptotically.
2) When rainfall increases as the storm progresses, retention loss tends towards some upper limit associated with the antecedent soil moisture in the catchment. It implies that the distribution of direct runoff volumes in extreme annual floods has the same asymptotic behaviour as the distribution of maximum annual precipitations (all data is expressed in millimeters). For simplicity, such parallelism between rainfall and discharge distributions is taken up to a return period T_g (usually 10 or 20 years).

   $$Qd(T) = Qd(T_g) + a_p(d)\left[u(T) - u(T_g)\right] \qquad (T > T_g) \qquad \text{(FR-1)}$$

   where $u(T)$ is a reduced Gumbel variable
3) The unit flood hydrograph or average transfer function from rainfall excess to streamflow is invariant with the magnitude of the rainfall. Peak discharge *Q* is therefore derived from Eq. (FR1) and the mean shape factor $\bar{r}$ of the hydrograph:

   $$Q(T) = \bar{r}Qd(T_g) \quad \text{with} \quad \bar{r} = mean(Q/Qd) \qquad (T > T_g) \qquad \text{(FR-2)}$$

ii) SPEED method

The SPEED method (Cayla, 1993) is based on similar hypotheses to those underpinning the Gradex method: use of a Gumbel distribution for rainfall, and parallelism between rainfall and discharge distributions up to return period (each additional volume of rainfall is totally converted into runoff):

$$Q(T) = \frac{P(T) - P_0}{12} S^{0.75} \qquad \text{(FR-3)}$$

where:

- $Q(T)$ and P(T) are the peak discharge (m^3/s) and the daily rainfall (mm) related to the return period T
- P_0 is the rainfall threshold (mm) related to the saturation of the catchment
- S is the catchment area (km^2)

The parameter P_0 is assessed from a graph with both $Q^*(T)$ and $P(T)$ distributions (Q^* is the reduced discharge: $Q^*=12\ Q/S^{0.75}$). When a difference of slope is detected on the rainfall distribution at a return period T_0 (with a parallelism between Q and P distribution up to T_0), P_0 is the interception value: P_0 = P(T_0) - $Q(T_0)$.

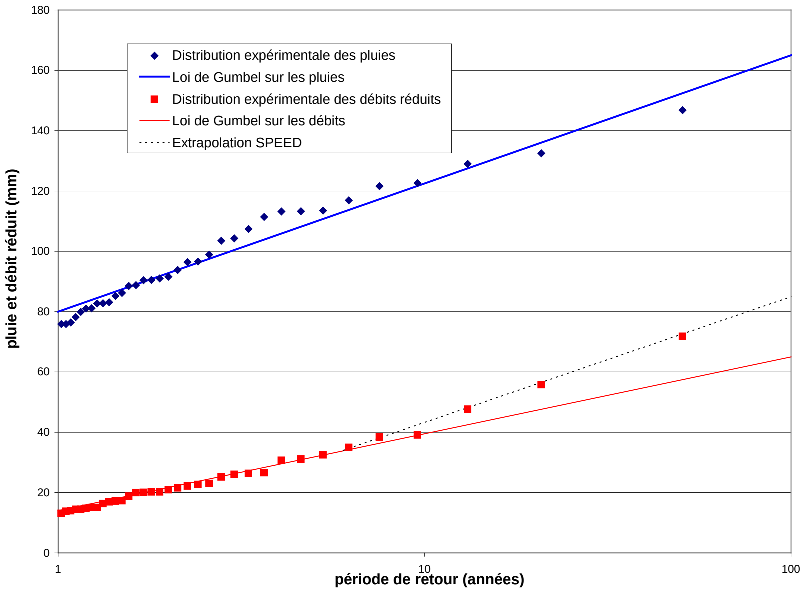

Figure FR1 Speed extrapolation on the Collobrier catchment.

iii) Agregee model

The Agregee model (Margoum *et al.*, 1994; Lang, 1997) leans heavily on the gradex model. It is based on two simple premises: the first, exactly the same as in the gradex method, assuming that, beyond a certain depth of rainfall, the infiltration loss ceases to increase on average; the second assumption is that the rainfall distribution function displays an asymptotically exponential behaviour. The purpose of the model is to determine all frequent and rare flood hydrographs up to a return period of 10,000 years, for studying catchment hydraulics.

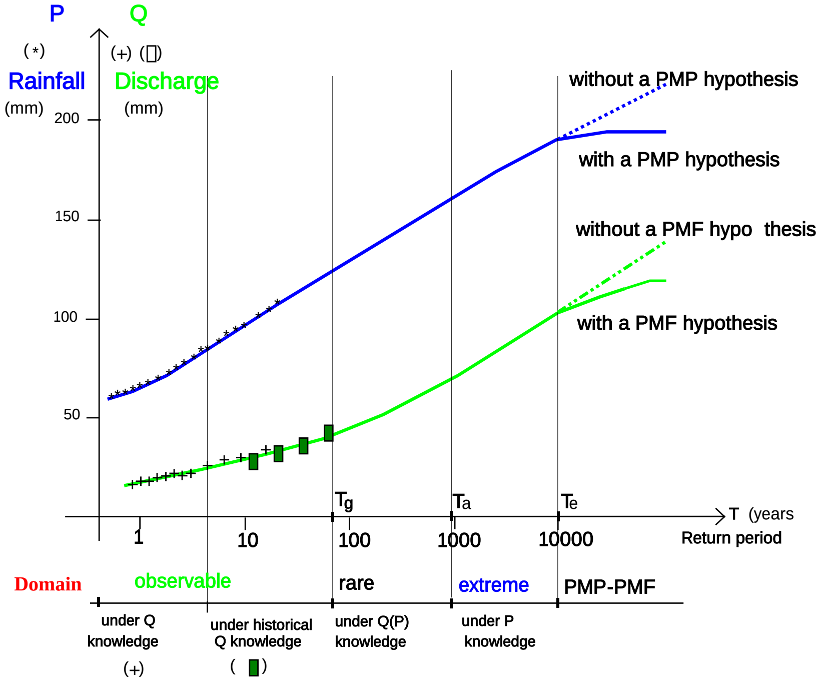

Figure FR2 Domains studied by the Agregee model.

One of the strong points of the model compared to the Gradex method is its good mathematical formulation of the progressive nature of the mean discharge distribution, providing a continuous relationship between three different flood domains (see Figure FR2): (i) the observable domain [0; T_g] in which discharge observations are the most pertinent (with the possibility of including historical flood data); (ii) the rare domain [T_g; T_a] in which rainfall data gradually replaces runoff data; (iii) the extreme domain [T_a ; T_e] concerned with the asymptotic behaviour between the flood and the rainfall distributions. The PMP/PMF method may possibly take over the recurrence interval T_e for estimating the Probable Maximum Flood. The Agregee model also incorporates certain theoretical results from the study and composition of the asymptotic branches of statistical models to improve the estimate of peak discharge and determination of design hydrographs. The Agregee and the Gradex method yield similar results from extreme floods [1000; 10,000 years], for estimating design floods. Beyond the return period T_g ($T > T_g$), the mathematical relationship for the average discharge Q_d on duration d, is the following:

$$Qd(T) = Qd(T_g) + \frac{a_e(d)}{K_p - K_q}\left\{K_p \; Ln\left[\frac{T + K_p}{T_g + K_p}\right] - K_q \; Ln\left[\frac{T + K_q}{T_g + K_q}\right]\right\} \qquad \text{(FR-4)}$$

with:

$K_p = [a_e(d) / a_p(T_g, d) - 1] \, T_g$ and $K_q = [a_p(T_g, d) / a_q(T_g, d) - 1] \, T_g$

$$a_e(d) = \lim_{T \to \infty} a_p(T_g, d) \qquad \text{(FR-5)}$$

$$a_p(T, d) = \frac{\partial Pd(T)}{dLnT}(T = T_g) \quad \text{and} \quad a_q(T_g, d) = \frac{\partial Qd(T)}{dLnT}(T = T_g)$$

where the parameters $a_p(T, d)$ and $a_q(T, d)$, are the slope of the distribution (respectively for rainfall and discharge) within a Gumbel graph, for the return period T. When rainfall is Gumbel distributed ($a_p(T,d)$ is a constant equal to $a_e(d)$), Eq. (FR4) is replaced by (with K_p = 0):

$$Qd(T) = Qd(T_g) + a_e(d) \; Ln\left[1 + \frac{a_q(T_g, d)}{a_e(d)} \frac{T - T_g}{T_g}\right] \qquad \text{(FR-6)}$$

which has been proposed by Michel (1982).

Regional methods

iv) The QdF models

The flood-duration-frequency (QdF) analysis is a similar approach than [?to the] the intensity-duration-frequency (IdF) model commonly used for rainfall analysis. It allows the temporal variability of floods to be described. Galéa and Prudhomme (1997) proposed a multi-duration continuous model which describes the different distributions $Qd(T)$ as a function of duration d: $Q(d,T)$. A regional QdF model based on the index-flood method was developed by Javelle *et al.* (2002):

- QdF model: $Q(d,T) = Q(d{=}0,T)/[1+d/\Delta]$

  where Δ is the characteristic flood duration of the basin
- Regional dimensionless distribution: $Q^*_{\text{region}}(d{=}0,T)$ from all stations k of the region with $Q_k(d{=}0,T)/\mu_k$

  where μ_k is the index flood which can be derived from the physiographical characteristics of the catchment
- Unscaled QdF curves: $Q(d,T)_{target\,site} = \left(\dfrac{Q^*_{region}(d = 0, T)}{1 + d / \Delta_{target\,site}}\right)\mu_{target\,site}$

v) Regional Bayesian POT model

Ribatet *et al.* (2007) proposed a combination of regional and local information from a Bayesian framework. They used a GP(θ) distribution for POT values, where θ = (u, β, γ) is the vector of parameters. A prior estimate π(θ) is based on the index flood assumption. A quantile estimate at site *k* is expressed as:

$$Q(T)^{(k)} = \mu_k \; Q^*_{region}(T)$$

where μ_k is the index flood. Therefore, all sites *k* from an homogeneous region (except target site *i*) are used to estimate the reduced parameters:

$$u^*_k = u_k / \mu_k \quad ; \quad \beta^*_k = \beta_k / \mu_k \quad ; \quad \gamma^*_k = \gamma_k / \mu_k$$

and the regional reduced GP(θ*) distribution:

$$\log(u^*_{region}) = \frac{1}{k-1}\sum_{k \neq i} \log(u^*_k) \quad ; \quad \log(\beta^*_{region}) = \frac{1}{k-1}\sum_{k \neq i} \log(\beta^*_k) \quad ; \quad \gamma^*_{region} = \frac{1}{k-1}\sum_{k \neq i} \gamma_k$$

Prior distribution at site *i* is a GP(θ_i) distribution computed as:

$$u_i = u^*_{region} \, \hat{\mu}_i \quad ; \quad \beta_i = \beta^*_{region} \, \hat{\mu}_i \quad ; \quad \gamma_i = \gamma^*_{region}$$

Posterior distribution at site *i* is given by the Bayes theorem:

$$p(\theta | x) \propto p(x | \theta) \; \pi(\theta)$$

where *x* is the set of local POT flood values at site *i*.

Ribatet *et al.* (2007) compared this regional Bayesian model with the index flood model. The former appears to be less sensitive to the degree of homogeneity of the pooling group. It can be used with relatively large and homogeneous region to provide more accurate results.

vi) Regional approaches for extreme rainfall quantiles

Neppel *et al.* (2007) compared two different methods used to estimate extreme rainfall quantiles in Mediterranean part of France. The first one (Arnaud *et al.*, 2008) is based on the regionalization of the parameters of the Shypre model (see WG3: hourly rainfall stochastic generator), on the basis of daily rainfall information. The second one is based on a regional GEV distribution, from a pooling of reduced samples of annual daily maximum at *k* sites. Independence of samples is achieved by discarding values from the same day (within a year) and belonging to neighbouring places (less than 80 km). Homogeneity of the region is assessed by L-moments criteria. The two approaches give similar results from extreme rainfall (less than 20% for the 1000 year rainfall). Both methods show that the heavy tail of the daily maximum annual rainfall distribution deviates from the exponential distribution.

2. Data

2.2 Flood data

The national HYDRO database, available on the internet at (http://www.hydro.eaufrance.fr/), gives free access to the daily discharge series of the French hydrometric network (about 3,000 stations). Information on regime is available (mean flow, low flow and floods). Flood quantile estimates are also available, between two to 50 years, from a Gumbel distribution on annual maxima.

3. Discussion

3.1 Purpose and areas of application

The standard applications of flood frequency analysis are related to:

- Urban hydrology: a simple local approach is used to estimate the 10-year rainfall (from a Gumbel distribution), which is then converted into the 10-year discharge by rational formula or SCS method.
- Flood hazard mapping, design of hydraulic structures: the 100-year flood is often estimated from a Gumbel distribution or the Gradex-Agregee method.

- Design flood for large dams: the 1000- or 10,000-year flood was estimated from the Gradex method. For several years, new simulation approaches (see WG3: Shyreg and Schadex methods) have aalso been applied.

Estimation on ungauged sites is usually based on a simple interpolation between quantile estimates at neighbouring sites (using regression formula with the catchment area) or the use of some QdF models.

The other approaches (use of historical data, regional approaches based on the pooling of data from homogeneous region, regionalization of simulation methods) were limited to case studies within research project. The Shypre-Shyreg method is a first attempt to apply “modern” techniques at a national scale.

3.2 Main features, merits and drawbacks

A guide for estimating the 100-year floods (Lang and Lavabre, 2007) presented the different flood frequency methods used in France. As there is a need for some homogenization of tools, a national project ExtraFlo (2009-2012) has been funded:

https://extraflo.cemagref.fr/extraflo-project-feb-2009-jan-2013/view?set_language=en

It has very similar aims to FloodFreq, especially as regards specifying the applicability of the various methods and drawing up avenues of research for the development of the methods, and in particular with regard to taking them into account in the context of the effects of climatic change. One specific point on the ExtraFlo project is to also add the following to the comparison methods based on proxy data on floods: hydro-geomoporphology and paleo-hydrology.

4. Case studies

Rainfall mapping in France

The regionalization of the parameters of the Shypre model (see WG3) is based on daily rainfall information, as the regionalization of the parameters of the rainfall-runoff model is based on hydrogeological and landuse information. Map of rainfall quantiles is already available at a 1 km^2 scale.

5. Plans for future development

Regionalization of the parameters of the Shypre model

This work is currently in development by Arnaud *et al*. (Cemagref, Aix). The aim is to provide an assessment of flood quantiles $Q(d,T)$ from d = 1 to 72 hours, and T = 2 to 1000 years. The map of discharge quantiles is looking currently at a set of selected catchments.

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GR – Greece (Andreas Efstratiadis, Lampros Vasiliades and Athanasios Loukas)

1. Description of method

The striking relief patterns, the long and intricate coastline, and the abundance of islands in Greece lead to the formation of numerous small-sized, steep hydrological basins. Typically, these are crossed by streams with ephemeral flow, which are affected by flash floods. The most important rivers, which have permanent discharge, are found in the western and northern part of the country. With few exceptions, their flow is regulated via dams, including all transboundary rivers that cross the Greek border. Therefore, the hydrological regime of most of the large rivers in Greece is heavily modified, which is of particular concern as regards the temporal distribution and spatial extent of floods.

The estimation of flood probability and risk can theoretically be offered through the statistical analysis of continuous, or finely resolved, discharge records with an appropriate length, sufficient to include a sample of representative extreme flows. Yet, systematic and reliable flow data in Greece is scarce. In addition, flow measurements are never enough to allow for the estimation of design magnitudes that correspond to relatively large return periods. Moreover, flood discharge data and, specifically peak flows, are highly uncertain, since they typically derive from stage-discharge formulas that do not capture flow measurements during flood events.

The evident alternative of the engineering practice is the use of hydrologic [hydrological?] models, with rainfall input data and parameters that are related to the physiographic characteristics of the watershed, to generate “synthetic” flood hydrographs. The need to use rainfall data as the basis of hydrologic design becomes even more evident in the study of engineering structures and urban water management systems that modify the natural environment, so that past flood records are no longer representative of the future modified system (Koutsoyiannis and Langousis, 2011).

For the above reasons, great emphasis is placed on the probabilistic modelling of extreme rainfall, which has a crucial role in flood risk estimation. The construction of rainfall intensity-duration-frequency (idf) relationships (“ombrian” curves) is one of the most common practical tasks related to the probabilistic description of extreme rainfall. Several forms of such relationships are found in the literature, most of which have been empirically derived and validated by long use in hydrologic practice. Yet, attempts to give them a theoretical basis have often used inappropriate assumptions and resulted in oversimplified relationships that are not good [?ideal] for engineering studies.

Koutsoyiannis et al. (1998) proposed a generalized framework for constructing idf curves, consistent with the theoretical probabilistic foundation of the analysis of rainfall maxima. Specific forms of this formula are explicitly derived from the underlying probability distribution function of maximum intensities. The formulation of idf relationships constitutes an efficient parameterisation, facilitating the description of the geographical variability and regionalisation of idf curves. Moreover, it allows the incorporation of data from non-recording stations, thus remedying the problem of establishing idf curves in places with a sparse network of rain-recording stations, using data of the denser network of non-recording stations.

Until recently, the Gumbel distribution has been the prevailing model for quantifying risk associated with extreme hydrological events (rainfall and, rarely, discharge) in Greece. Several arguments, including theoretical reasoning and empirical evidence, are supposed to support the appropriateness of the Gumbel distribution. In a number of studies, Koutsoyiannis (2004, 2005, 2007) questioned these arguments, thus proving that the Gumbel distribution is quite unlikely to apply to hydrological extremes and its application may misjudge the risk as it underestimates seriously the largest extreme rainfall amounts. Besides, he showed that hydrological records of typical length (some decades) may display a distorted picture of the actual distribution, suggesting that the Gumbel distribution is an appropriate model for hydrological extremes, which is not is not the case. New theoretical arguments based on comparisons of actual and asymptotic extreme value distributions as well as on the principle of maximum entropy indicate that the Generalized Extreme Value Type 2 (GEV2) distribution should replace the Gumbel distribution for the analysis of rainfall maxima. Similar conclusions are derived for the discharge maxima, although inthat case we have much less data [?far fewer] to investigate. In Fig. GR1 we plot the empirical vs. the theoretical distributions of annual maximum flows for two rivers in Greece, i.e. Acheloos (left) and Boeoticos Kephissos (right) with very different characteristics. Two probabilistic models are examined, the Gumbel and the GEV2, the parameters of which are estimated via the L-moments approach. It is obvious that the Gumbel model fails to represent the upper part of the sample properly, since it seriously underestimates the return periods of the highest observed events.

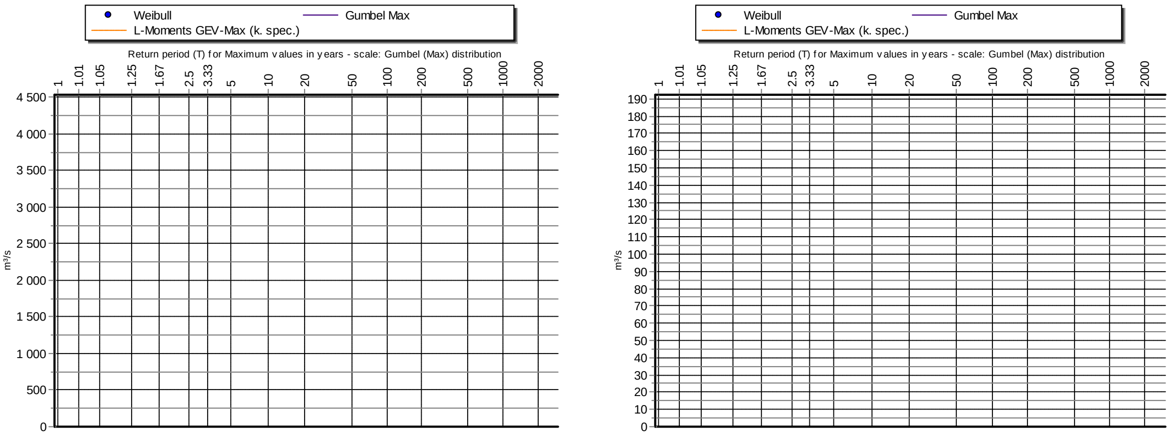

Figure GR1 Plots of empirical vs. theoretical (Gumbel and GEV-II) distributions for the statistical anlysis of annual maximum daily flows of Acheloos river (upstream of Kremasta dam; left chart) and Boeoticos Kephissos river (at the outlet; right chart).

Regionalisation techniques for estimating flood quantiles at gauged sites have been intensively used in the flood frequency literature. These methods require significant amounts of reliable flood flow data, either to provide adequate sample sizes for the statistical and the regional approach, or to calibrate adequately the basin rainfall-runoff response for the simulation approach.

2. Data

During the last 10-15 years, the hydrological monitoring infrastructure in Greece has been rapidly shirked [?disregarded] and degraded. In the past, numerous authorities, organizations and institutions have been involved in the collection of river flow data, mainly in terms of stage observations (continuous stage records are rather few). Yet, the organization of these data is far from satisfactory and the outdated stage-discharge relationships make the usefulness of the data questionable.

Recently, the Ministry of Environment developed a web-based platform for the management and operation of the National Databank for Hydrologic and Meteorological Information, which provides free data and software for hydrological applications (http://www.hydroscope.gr/). Until now, however, the database has not contained finely resolved discharge data, except from a limited number of daily flow records.

3. Discussion

Within flood modelling, statistical tools are applied for multiple purposes, such as:

- the processing and analysis of hydrological and hydraulic data (e.g. construction of stage-discharge relationships);
- the representation of rainfall (model input) through statistical and stochastic approaches (e.g. intensity-duration-frequency curves, synthetic storms, space-time stochastic modelling, etc.);
- the estimation of rainfall-runoff model parameters through regionalization techniques.

4. Case studies

Several studies have focused on regionalization techniques. Mimikou and Gordios (1989) examined the spatial variation of the mean annual flood of both mean daily and instantaneous extremes and the variation of the parameters of the Extreme Value Type 1 (EV1) distribution for catchments in the northwest and west regions of Greece by using multiple regression techniques with physiographic and climatological characteristics of the catchments. The catchment characteristics were the following: drainage area, mean annual areal precipitation, stream frequency, main stream slope and length, intensity of the one-day rainfall of a five-year return period, and a soil type index. The EV1 distribution has been found to describe adequately the annual frequency distributions of the daily and of the standardised by-their-mean-value daily extremes of the catchments. Based on the regional models for the parameters of the distribution, annual flood frequency curves, and thus flood quantiles of the assumed distribution, could be derived. The developed regional models were successfully used in predicting with satisfactory accuracy the mean annual floods and flood quantiles, needed in hydrological design, for ungauged catchments within the region studied (Mimikou and Gordios, 1989). In another study (Mimikou, 1990) regionalization was performed for several hydrological variables in north-western Greece. The spatial variation of parameters of suspended sediment-water discharge rating curves, of maximum observed flood discharges, of lag times and hydrograph peaks for a certain storm duration, of parameters of flow duration curves and of mean annual floods for basins in the northwest and west of Greece were significantly explained in terms of physiographic and climatological characteristics of the basins by using multiple regression techniques. The developed regional models were successfully used in predicting hydrological variables for ungauged basins within the regions studied for western Greece. In another study, a regional technique for extreme rainfall and runoff prediction was presented (Mimikou et al., 1994). This study is demonstrated for four watersheds located in western and north-western Greece, and uses five nomographs in which flood and storm characteristics are associated. Design flood peak and volume values were derived, once the return period, storm duration and depth had been determined. Problems of basin non-linearity do not affect the method which proved to be accurate, fast and simple. These qualities render the method useful for engineering and research applications, especially in ungauged basins (Mimikou et al., 1994).

5. Plans for future development

Greece is planning to collect more flow data and developing tools to analyse and predict flood flows and frequencies. In particular, a research project called Deukalion is now running; it aims to develop a set of physically-based (by means of field observations) tools and methodologies associated with modelling and forecasting of extreme rainfall events and the subsequent flood events, which will be specifically adapted to the peculiarities of the hydroclimatic and geomorphological conditions of Greece. The key component of the project is the development of a pilot river basin network, equipped with adequate gauging systems, so that it provides the necessary infrastructure for the systematic investigation of the overall components related to flood generation. This network will comprise some new hydrometric stations and also include existing stations in Greece and Cyprus.

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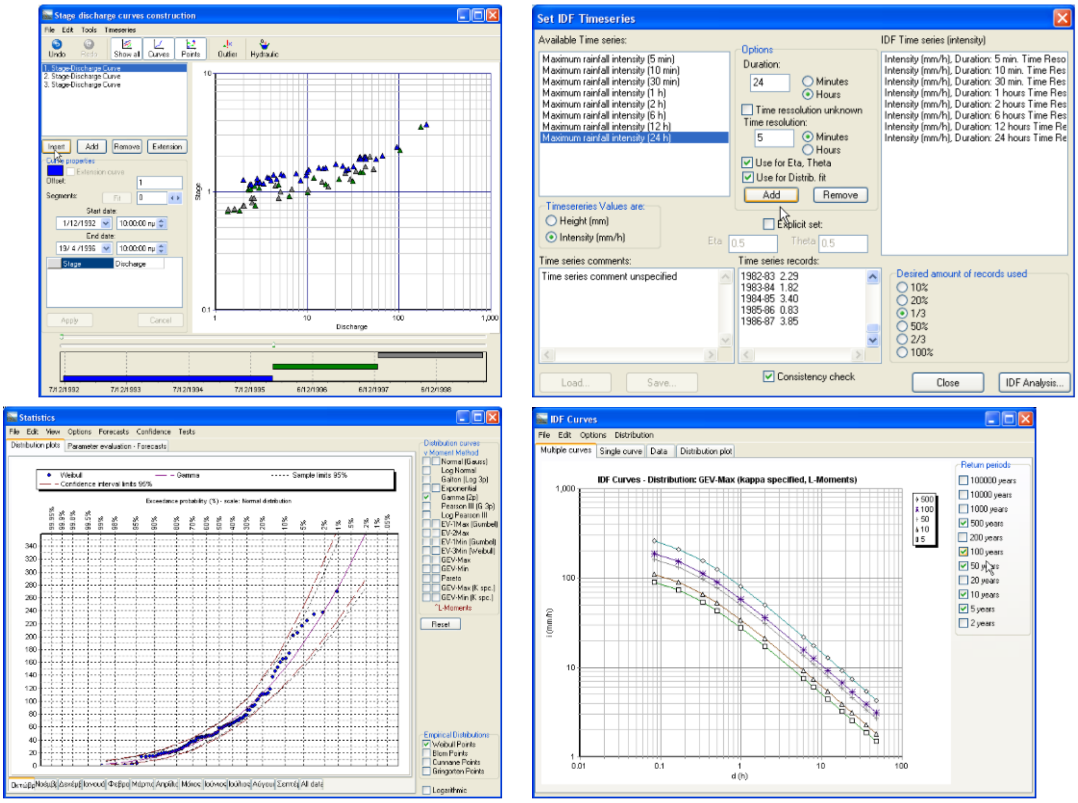
Appendix – Description of software

Hydrological data processing and analysis (Hydrognomon)

Hydrognomon is a general-purpose software tool for the processing and analysis of hydrological data. It is an open source application running on standard Microsoft Windows platforms, which it is also part of the openmeteo.org framework. Data are imported through standard text files, spreadsheets or by typing. Standard hydrological data processing techniques include time step aggregation and regularization, interpolation, regression analysis and infilling of missing values, consistency tests, data filtering, graphical and tabular visualisation of time series, etc. It supports several time steps, from the finest minute scales up to decades; specific cases of irregular time steps and offsets are also supported. The program employs typical hydrological applications, such as homogeneity tests, evapotranspiration modelling, stage-discharge analysis, areal integration of point data, of hydrometric data processing, and lumped hydrological modelling.

Specifically, the statistical modules of Hydrognomon provides a number of typical and advanced numerical tools for data exploration, fitting of distribution functions, statistical prediction, Monte-Carlo simulation, determination of confidence limits, analysis of extremes, and construction of ombrian (intensity-duration-frequency) curves. All the above tools, including the stage-discharge analysis module, can be used within various stages of flood modelling. Characteristic screenshots are shown in Fig. GR2.

The software is freely available at http://hydrognomon.org/.



1. Stage-Discharge Curve
2. Stage-Discharge Curve
3. Stage-Discharge Curve

Offset: 1
Segments: 0
Start date: 1/12/1992 10:00:00 πμ
End date: 19/ 4 /1996 10:00:00 πμ

Available Time series:
Maximum rainfall intensity (5 min)
Maximum rainfall intensity (10 min)
Maximum rainfall intensity (30 min)
Maximum rainfall intensity (1 h)
Maximum rainfall intensity (2 h)
Maximum rainfall intensity (6 h)
Maximum rainfall intensity (12 h)
Maximum rainfall intensity (24 h)

Duration: 24 ○ Minutes ● Hours
☐ Time ressolution unknown
Time resolution: 5 ● Minutes ○ Hours
☑ Use for Eta, Theta
☑ Use for Distrib. fit
☐ Explicit set:
Eta 0.5 Theta 0.5

Timesereries Values are:
○ Height (mm)
● Intensity (mm/h)

Time series comments:
Time series comment unspecified

Time series records:
1982-83 2.29
1983-84 1.82
1984-85 3.40
1985-86 0.83
1986-87 3.85

IDF Time series (intensity)
Intensity (mm/h), Duration: 5 min. Time Reso
Intensity (mm/h), Duration: 10 min. Time Res
Intensity (mm/h), Duration: 30 min. Time Res
Intensity (mm/h), Duration: 1 hours Time Res
Intensity (mm/h), Duration: 2 hours Time Res
Intensity (mm/h), Duration: 6 hours Time Res
Intensity (mm/h), Duration: 12 hours Time Re
Intensity (mm/h), Duration: 24 hours Time Re

Desired amount of records used
○ 10%
○ 20%
● 1/3
○ 50%
○ 2/3
○ 100%

☑ Consistency check

Distribution curves
☐ ☐ Normal (Gauss)
☐ Log Normal
☐ Galton (Log 3p)
☐ ☐ Exponential
☑ Gamma (2p)
☐ Pearson III (G 3p)
☐ Log Pearson III
☐ ☐ EV-1Max (Gumbel)
☐ ☐ EV-2Max
☐ ☐ EV-1Min (Gumbel)
☐ ☐ EV-3Min (Weibull)
☐ ☐ GEV-Max
☐ ☐ GEV-Min
☐ ☐ Pareto
☐ ☐ GEV-Max (K spc.)
☐ ☐ GEV-Min (K spc.)
^L-Moments

Empirical Distributions
☑ Weibull Points
☐ Blom Points
☐ Cunnane Points
☐ Gringorten Points
☐ Logarithmic

Return periods
☐ 100000 years
☐ 10000 years
☐ 1000 years
☑ 500 years
☐ 200 years
☑ 100 years
☑ 50 years
☐ 20 years
☑ 10 years
☑ 5 years
☐ 2 years

Figure GR2 Screenshots of the statistical modules of Hydrognomon: stage-discharge analysis (top left); fitting of empirical and theoretical distribution functions and estimation of confidence limits (bottom left); data import for idf analysis (top right); construction of rainfall intensity-duration relationships for various return periods (bottom right).

Stochastic disaggregation of fine-scale rainfall (Hyetos)

Hyetos performs stochastic simulation of single-site fine-scale rainfall based on the Bartlett-Lewis point process model. It operates on several modes and combinations of them (depending on data availability), such as the operational or the testing mode, and simple sequential simulation or disaggregation. In the latter case it disaggregates given daily rainfall depths into hourly values.

The methodological framework, developed by Koutsoyianns and Onof (2000, 2001), combines an existing rainfall simulation model of the Poisson cluster type along with an appropriate technique for modifying the rainfall model output, thus performing disaggregation. Specifically, it uses the Bartlett-Lewis rectangular pulses rainfall model as a background stochastic model for rainfall generation. Repetition is first carried out to derive a synthetic rainfall series, which resembles the given series at the daily scale. This step focuses on the wet/dry pattern and the intensities separately. In a second step, an appropriate procedure, called proportional adjusting procedure, is applied to make the generated hourly series fully consistent with the given daily series without affecting the stochastic structure implied by the model. The model was successfully applied with data sets of several regions, both with dry and wet climates.

The software is freely available at http://www.itia.ntua.gr/en/softinfo/3/.

Multivariate disaggregation of rainfall (MuDRain)

MuDRain gets daily rainfall data series at several sites and disaggregates them into hourly data series, also utilising existing hourly data of one or more neighbouring rain gauges. It employs an original methodology developed by Koutsoyiannis et al. (2003), which involves the combination of several univariate and multivariate rainfall models operating at different time scales, in a disaggregation framework that can appropriately modify outputs of finer time scale models so as to become consistent with given coarser time scale series; an outline of the methodology is shown in Figure GR3. Potential hydrologic applications include enhancement of historical data series and generation of simulated data series. Specifically, the software can be applied to derive spatially consistent hourly rainfall series in rain gauges where only daily data are available. In addition, in a simulation framework, the methodology provides a way to take simulations of multivariate daily rainfall (incorporating spatial and temporal non-stationarity) and generate multivariate fields at fine temporal resolution. The methodology results in good preservation of important properties of the hourly rainfall process such as marginal moments, temporal and spatial correlations, and proportions and lengths of dry intervals, and in addition, a good reproduction of the actual hyetographs.

The software is freely available at http://www.itia.ntua.gr/en/softinfo/1/.

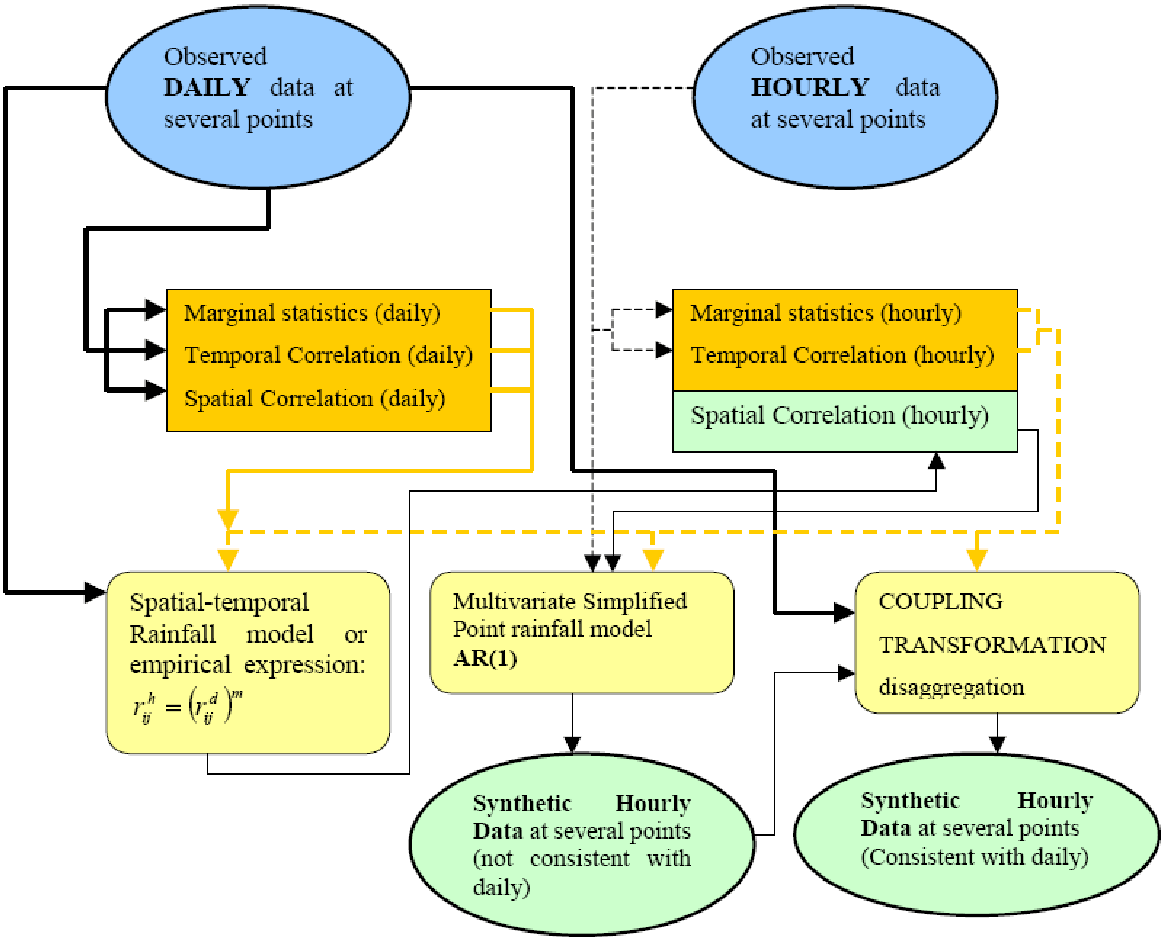


Figure GR3 Outline of the modelling scheme implemented within MuDRain (Fytilas, 2002).*IT – Italy (VA.PI. and CUBIST national research grants. Attilio Castellarin)*

IT – Italy (VA.PI. and CUBIST national research grants. Attilio Castellarin)

1. Description of method:

Between the 1980s and the first years of the 21th century the GNDCI (National Group on Hydrogeological Disasters Prevention, http://www.gndci.cnr.it/; http://www.idrologia.polito.it/gndci/Vapi.htm) of the Italian National Research Council, inspired by the UK Flood Studies Report (FSR, NERC, 1975), promoted the nationwide research project VA.PI. ("VAlutazione PIene", Flood Estimation). The VA.PI. project aimed to identify a national approach to the frequency analysis of hydrological extremes (rainfall depths in a given duration and flood flows). This document briefly illustrates the regional flood frequency estimation procedure which was identified within the VA.PI. project.

The VA.PI. procedure for design flood estimation is illustrated in a series of publications, which refers to a compartmentalization of Italy into hydrological macro-regions (see Fig. IT1).

Figure IT1 Compartmentalization of Italy into hydro-climatic macro-areas (1^{st} hierarchical level).

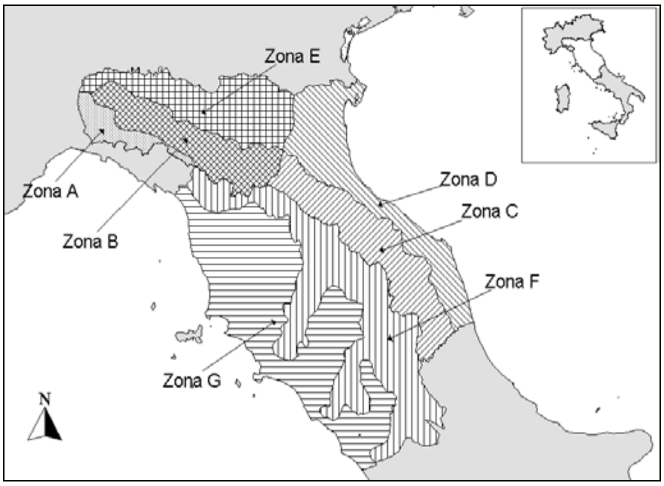


Figure IT2 Central Italy, homogeneous sub-areas (2nd hierarchical level).

The VA.PI. procedure adopts a hierarchical index-flood approach (see e.g., Gabriele and Arnell, 1991) structured into three hierarchically nested levels that reflect three nested compartmentalisations of Italy. The first level refers to the hydrologically homogeneous macro-zones for which the third and higher order moments are assumed to be constant (e.g., skewness and kurtosis coefficients or L coefficients, etc.). The second level refers to homogeneous sub-zones where also the second order moment is assumed to be constant (e.g., coefficient or L coefficient of variation). The third level refers to the areas (may or may not be nested into the previous ones) with homogeneous flood formation mechanism in terms of the first order moment (i.e., mean of the distribution or index-flood). For these areas multiregression models for index-flood prediction in ungauged sites were identified by the VA.PI. project. Examples of compartmentalizations are reported in Figures IT1, IT2 and IT3.

The VA.PI. project considered annual maximum series of peak flows published by the former Italian hydro-meteorological Service (SIMN) and two probabilistic models were used as parent distributions: the Generalised Extreme Value (GEV) and Two Components Extreme Value (TCEV) distributions (see next subsections).

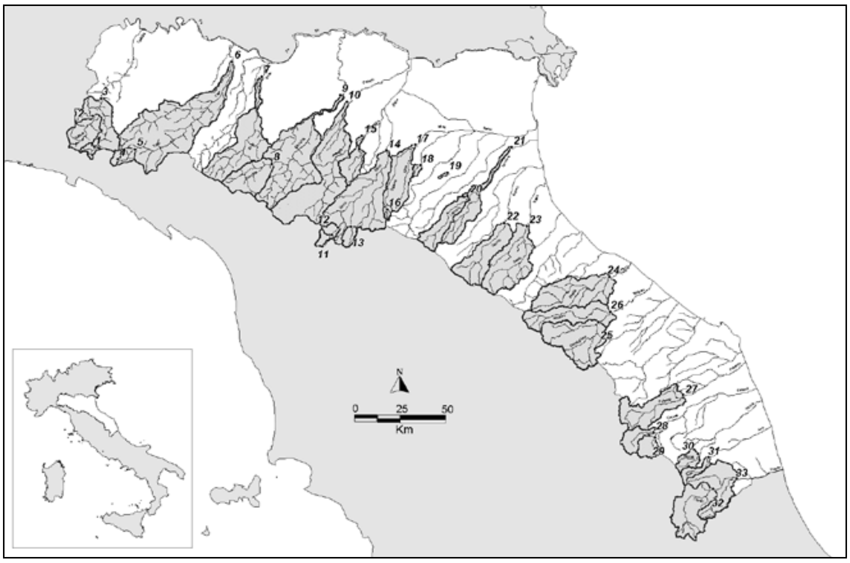


Figure IT3 Sub area considered for developing multiregression model (2).

The VA.PI. project resulted in a series of National reports:

- VERSACE P., FERRARI E., FIORENTINO M., GABRIELE S., ROSSI F. "La valutazione delle piene in Calabria". CNR-GNDCI, LINEA 1, CNR-IRPI, Geodata, Cosenza, 1989.
- CAO C., PIGA E., SALIS M., SECHI G.M. "Valutazione delle piene in Sardegna". Rapporto Regionale Sardegna, CNR-GNDCI, LINEA 1, Istituto di Idraulica, Università di Cagliari, 1991.
- COPERTINO V., FIORENTINO M. (a cura di) "Valutazione delle piene in Puglia", CNR-GNDCI, Potenza, 1992.
- CANNAROZZO M, D`ASARO F., FERRO V. "Valutazione delle piene in Sicilia", CNR-GNDCI, Palermo, 1993.
- ROSSI F, VILLANI P. (a cura di) "Valutazione delle piene in Campania", Rapporto Regionale Campania, CNR-GNDCI, 1994.
- VILLI V., BACCHI B. "Valutazione delle piene nel Triveneto" , CNR-GNDCI, Padova-Brescia, 2001.

and a number of scientific papers on national and international journals.

1.1 Identification of homogeneous pooling-groups of sites

Pooling groups of sites are fixed regions in the VA.PI. procedure. Their delineation in structured in three hierarchical levels as described above. The hydroclimatic macrozones and sub-zones are identified on the basis of various sources of information (e.g., mainly orographic divides, altitude, distance from the coastline, catchment orientation, frequency regime of rainfall annual maxima, see Castellarin et al., 2001; Brath et al., 2003). Homogeneity in terms of skewness and Kurtosis coefficients (1st hierarchical level) and coefficient of variation (2nd hierarchical level) is tested through Monte Carlo procedures (see e.g., Hosking and Wallis, 1993; Castellarin et al., 2008). Examples of macro-zones and subzones are reported in Figures IT1, IT2, and IT3. Enhancements of the VA.PI. procedure concerning the identification of poling groups of sites are reported in the literature for Italian regions (e.g. focused-pooling instead of fixed regions is illustrated in Castellarin et al., 2001).

1.2 Estimation of the index flood or site-specific scale factor

The VA.PI. procedure defined the index-flood as the mean annual flood. The GNDCI proposed a number of models (multiregression statistical models and conceptual models, see Brath et al., 2001) for predicting the index-flood in ungauged sites. An example for the study region illustrated in Figure IT3 is reported below,

$$\hat{\mu}_X = 2.904 \cdot 10^{-5} A_{rid}^{1.299} {\mu_{H,1}^{r}}^{3.504} L^{-0.778}$$

where $\hat{\mu}_X$ is the index-flood estimate (m^3/s), A_{rid} the low permeability portion of the catchment area (km^2), $\mu_{H,1}^{r}$ the mean of point-rainfall annual maxima for 1-hour duration averaged over the catchment (mm), and L the main stream length (km).

1.3 Choice of a frequency distribution

The VA.PI. procedure considers to the Generalised Extreme Value (GEV) and Two Components Extreme Value (TCEV) distribution and recommends the use of the TCEV distribution (Rossi et al., 1984). The TCEV distribution is a 4-parameter distribution that assumes that floods arise from a mixture of two exponential components. The cdf of TCEV distribution can be written for the dimensionless variate *x*' (i.e., flood value standardized by the index-flood) in terms of three parameters Λ_*, θ_* and Λ_1, and a function of these three parameters η,

$$F_{X'}(x') = \exp\left[-\Lambda_1 \exp(-\eta \cdot x') - \Lambda_* \Lambda_1^{1/\theta_*} \exp\left(-\eta \cdot x'/\theta_*\right)\right].$$

1.4 Estimation of the frequency distribution

The VA.PI. procedure recommends the maximum likelihood method for the estimation of TCEV parameters. Parameters Λ_*, θ_* control skewness and kurtosis of the distribution and were estimated for each hydroclimatic macro-zone delineated in the project (1st hierarchical level). Parameter Λ_1 control the variance of the TCEV and was estimated on a regional level for the homogeneous subzones identified within the project (2nd hierarchical level). TCEV parameters were mapped for all hydroclimatic zones of Italy.

2. Data

2.1 Catchment descriptors

The catchment descriptors used within the VA.PI. project are traditional descriptors reported by SIMN for Italian system of gauged basins, namely: drainage area; impervious portion of the drainage area; highest, mean and minimum elevations; mean annual precipitation and runoff.; presence of reservoirs. These descriptors are reported on the Italian Hydrological Yearbooks, which were formerly published by SIMN (http://www.apat.gov.it/site/en-GB/Projects/Hydrological_Yearbooks/default.html) and are now published for Italian administrative districts by Regional Environmental Protection Agencies (ARPA, see e.g. http://www.arpa.emr.it/sim/?idrologia/annali_idrologici).

2.2 Flood data

The VA.PI. project referred mainly to annual maximum series of instantaneous peak flows and daily discharge for a set of about 300 catchments (average record length 30÷35 years). Data are now accessible in PDF (not full-text) at the following site (Hydrological Yearbooks from 1921 to early nineties): http://www.annali.apat.gov.it/site/it-IT/

Data collected in more recent years are now published by the ARPA's. Data collected at some gauging stations can also be accessed in realtime, see for Emilia-Romagna:

http://www.arpa.emr.it/sim/?idrologia

3. Discussion

3.1 Purpose and areas of application

VA.PI. procedure has been adopted by Italian institutions and authorities dealing with water resources management, watershed planning and civil protection (e.g., basin authorities, civil protection agencies, etc.) to be used for flood frequency analysis and design flood estimation. Locally, more advanced procedures have been developed and adopted in combination with VA.PI.

3.2 Main features, merits and drawbacks

Nationwide coverage; hierarchical feature that improves the estimation of higher order moments; fixed and contiguous zones (makes the application to ungauged basins easier, but introduces boundaries and abrupt jumps in the growth curves); not up to date in terms of data (80's-90's).

4. Plans for future development

Since the end of the project the Italian scientific community dedicated a lot of efforts in the update and enhancement of the VA.PI. procedure locally and nationally. The most recent national research project which addressed this topic, in the general context of t he 'Prediction in Ungauged Basins' (PUB) research area, is the CUBIST Project (http://www.cubist.polito.it/).

The project focuses primarily on: the relaxation of the fixed regions hypothesis, the update and enhancement of catchment descriptors (e.g., analysis of SRTM 90m DEM) and flood data.

6. References

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Castellarin, A., Burn, D.H. and A. Brath (2001): Assessing the effectiveness of hydrological similarity measures for regional flood frequency analysis. *Journal of Hydrology*, 241(3-4), 270–285.

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Gabriele, S., N. Arnel (1991): A hierarchical approach to regional flood frequency analysis, *Water Resour. Res.*, 27(6), 1281–1289.

Institute of Hydrology (1999): *Flood Estimation Handbook*, 5 Volumes, Institute of Hydrology, Wallingford, UK.

Rossi, F., M. Fiorentino and P. Versace (1984): Two component extreme value distribution for flood frequency analysis. *Water Resour. Res.*, 20, 847–856.

LT – Lithuania (D. Sarauskiene and J. Kriauciuniene)

1 Description of method

1.1 Identification of homogeneous pooling-groups of sites

There are three hydrological regions (Figure LT1) in Lithuania (Western, Central and Southeastern). Rivers in Lithuania are divided according to the type of the river feeding and hydrological regime into three groups. Sources of river feeding are precipitation, snowmelt and groundwater. Types of river feeding in different regions are presented in Table LT1 (Gailiusis et al., 2001).

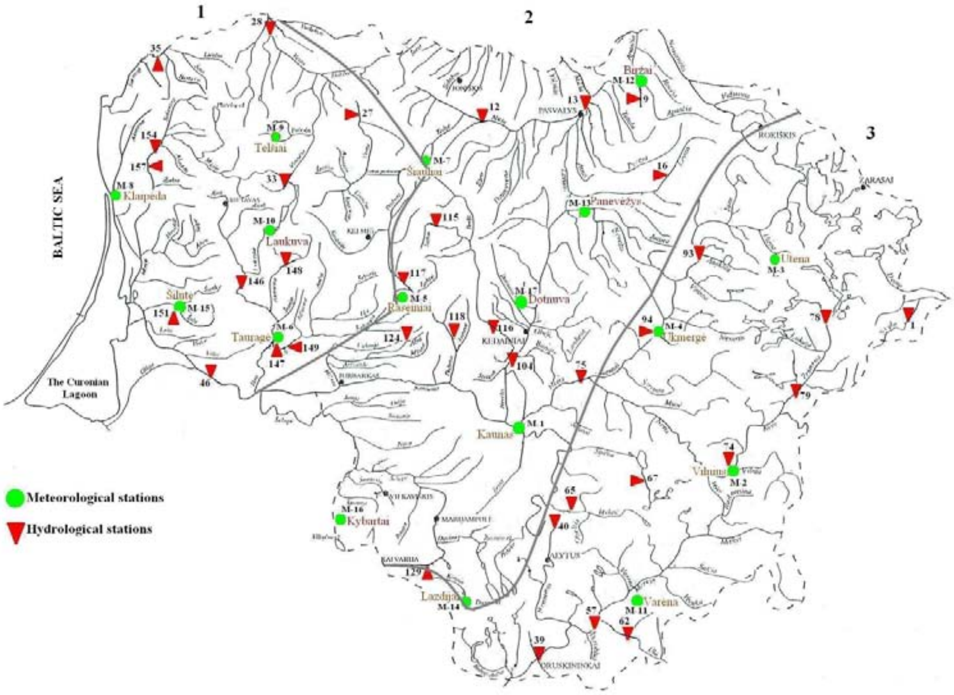

Figure LT1 Hydrological regions in Lithuania: Western (1), Central (2) and Southeastern (3).

Table LT1 Sources of river feeding in three hydrological regions of Lithuania

Hydrological regions of Lithuania	Feeding source in [%]		
	snowmelt	Precipitation	groundwater
Western	29	53	18
Central	43	41	16
Southeastern	27	28	45

The main source of river feeding in Western Lithuania is precipitation. The maximum discharges, resulting in the rain floods, often exceed discharges of spring floods. The type of river feeding in Central Lithuania is mixed. The feeding from the groundwater is not significant, smaller rivers dry out in the summer. A very irregular runoff distribution during a year is the main feature of the rivers in Central Lithuania. The rivers of Southeastern Lithuania have a prevailing subsurface feeding. The permeable sandy soils, that are widespread here, effectively absorb snowmelt and later gradually release, supplying rivers in the low water period. The annual runoff of Southeastern rivers is distributed rather equally. The rivers have one flood peak during the spring snowmelt period.

1.2 Estimation of the index flood or site-specific scale factor

The analysis of the spring flood runoff and the maximum discharges is performed for all gauging stations (Gailiusis et al., 2001). The generalized descriptions of the spring floods in three hydrological regions are carried out according to maximum discharges, dates, duration and volume of the runoff. A map of the territorial distribution of flood runoff hydromodule has been prepared. It enables the values of the spring flood runoff for the ungauged rivers to be determined.

The calculation methods for the expected value of the flood maximum discharge in ungauged rivers are based on genetic theory of surface runoff formation, equations LT-1 and LT-2, (Gailiusis et al., 2001). This theory reflects the natural “reason-consequence” relationships which form in a river catchment and which allow not only the processes in the catchment area during snowmelt to be assessed, but also the characteristics of the catchments areas. To date, two types of formulas are recommended in Lithuania:

1) *reduction* formula, which evaluates the reduction of the modules of maximum discharges when catchment area gets bigger:

$$Q_{p\%} = \frac{A_{p\%} \cdot A}{(A+b)^{n}} \cdot \delta_1 \cdot \delta_2; \qquad \text{(LT-1)}$$

2) *volumetric* formula, where flood maximum discharge is expressed as a function of flood volume (height of layer), duration and geometric form:

$$Q_{p\%} = \frac{K_0 \cdot h_{p\%} \cdot A}{(A+1)^{n}} \cdot \delta_1 \cdot \delta_2 \cdot \mu; \qquad \text{(LT-2)}$$

In these formulas the following parameters are used: Q_p – maximum discharge of $p_{\%}$ probability m^3/s; A_p – elementary maximum discharge of $p_{\%}$ probability, also called geographical parameter m^3/s; A – catchment area km^2; b – parameter for evaluation of the decreasing reduction in small catchments; n – index that characterizes reduction of maximum discharge; δ_1 – coefficient that evaluates decrease of maximum discharge because of impact of lakes and other water bodies; δ_2 – coefficient that evaluates decrease of maximum discharge because of impact of wetlands and forests in catchment area; K_0 – parameter that shows the intensity of spring flood; $h_{p\%}$ – $p_{\%}$ probability height of flood runoff [mm]; μ – coefficient that evaluates variance of statistical parameters of flood runoff and maximum discharge.

1.3 Choice of a frequency distribution

Lithuania does not have any recommendations or procedures for the use of specific frequency distributions. Until now, the normal distribution was the most widely used for calculation of statistical parameters for long data series of river discharges.

Analysis of different flood frequency distributions using long-term data from 32 water measurement stations (Sarauskiene and Kriauciuniene, 2011) was performed in order to estimate the best fit distributions for Lithuanian conditions. Five commonly used probability distributions: Gumbel (EV1), Generalized extreme value (GEV), log-Pearson type 3 (LP3), lognormal (LN) and three-parameter lognormal (LN3) were selected for the analysis statistical characteristics of observed flood data of Lithuanian rivers.

Statistical parameters of maximal discharges ($\overline{Q}_{max}$, C_v and C_s) have been calculated using the Method of Moments and Method of Maximum Likelihood. For the hydrological regions the following values and relations have been estimated:

- Western region: C_v =0.35-0.50; $C_s \sim Cv$
- Central region: C_v =0.40-0.60; C_s=2Cv
- Southeastern region: C_v =0.50-0.89; C_s=3.0-3.5Cv

The analysis revealed that spring flood data of individual rivers, as well as in the different regions, tended to have different best-fit probability distributions for the studied time periods, 1961-1990. The LP3 probability distribution best fitted actual data of the spring flood in the

Western region and the GEV – for the Central and Southeastern regions. For the period 1991-2008, the GEV was the probability distribution that received the highest ranks in all regions. LN and EV1 probability distributions appeared to be the least suitable (out of the five studied) for the modelling of the analyzed spring flood data.

2 Data

2.1 Catchment descriptors

Available catchment parameters for Lithuanian rivers (Gailiusis et al., 2001) are:

- streamgauge longitude, latitude, altitude
- minimum, maximum and mean elevation (m a.s.l.)
- drainage area (km2)
- presence of pervious soils, lakes, reservoirs, wetlands and forests (%)
- mean annual precipitation and runoff (mm)

2.2 Flood data

All hydrological data is owned by the Lithuanian Hydrometeorological Service under the Ministry of Environment (http://www.meteo.lt/english/services.php). Data type is AMS.

Researchers from Laboratory of Hydrology of Lithuanian Energy Institute collected the following characteristics of spring floods in 125 stations of Lithuanian rivers (Gailiusis et al., 2001):

- Basin areas (km^2)
- Observation period
- Dates of flood beginning, maximum and end
- Flood wave duration (days) till maximum and the total
- Volume of flood (mln. m^3) and part of flood volume in annual runoff (%)
- Flood runoff (mm)

3 Discussion

3.1 Purpose and areas of application

Analysis of applied statistical methods for flood-frequency analysis in Lithuania will be used for the design and exploitation of hydropower stations, dam safety analysis (flood-hazard mapping), and evaluation of the impact of climate change on flood characteristics.

A System of Flood Risk Assessment and Management is being created in Lithuania. Its first stage– Preliminary Assessment of Flood Risk – was implemented this year. During the second stage, precise maps of flood danger and flood risk will be created. The territories that can be inundated by 10, 1 and 0.1% probability floods will be defined and shown on maps with the scale 1:2 000 - 1:10 000.

3.2 Main features, merits and drawbacks

There are a lot of small hydroelectric power plants built on small rivers in Lithuania. For the existing hydroelectric power plants and hydrotechnical structures, as well as for the planned ones, the estimation of characteristics of certain probability flood is of great importance. Since small rivers often have short series of observation data or no data at all, it is possibile to use available flood characteristics of other rivers of the same homogenous region, applying flood frequency analysis. In such cases the river-analogues method is widely used in Lithuania.

3.3 Recommendations for users

For proper planning and design of civil engineering structures, knowledge of extreme floods (magnitude and frequency) is essential. Design discharge is defined for five classes of hydro technical structures. The smaller class number shows the greater importance of the structure, and then discharge is estimated for the maximum discharges of the smallest probabilities (p=0.01-1.0%). When maximum discharges are calculated for the 1st class structures (p=0.01%), a security amendment ΔQ_p has to be added:

$$\Delta Q_{p\%} = \frac{a \cdot E_{p\%}}{\sqrt{n}} Q_{p\%}$$

Where a is security coefficient, that shows a degree hydrological investigation of the river (a=1.0 for well investigated rivers, a=1.5 for little investigated rivers); n – number of years of observations; $E_{p\%}$ - dimension, that characterizes mean square error of discharge Q_P and that is determined depending on C_V and C_S/C_V values.

Value of a security amendment cannot exceed 20% of calculated $Q_{0.01\%}$ maximum discharge.

Applying of new flood-frequency analysis methods for Lithuanian rivers is useful for supplement of Technical Requirements for Construction Activities in Lithuania.

The results of the mentioned Flood Risk Assessment project will be crucial for risk assessment in the planned new settlements in river valleys.

5 Plans for future development

- to determine the impact of design of hydraulic structures on the curves of flood frequency distributions comparing the flood data in the same river.
- to apply L-moment diagrams to assess the regional probability distributions for Lithuanian hydrological regions.

6 References

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NO – Norway (Donna Wilson and Anne K. Fleig)

1. Description of method

The Norwegian Water Resources and Energy Directorate (NVE) has the national responsibility for providing guidelines for and approving flood estimates. The current valid guidelines were established in 2002 and are currently under revision. Here, we describe the methods as suggested in a Green Paper by NVE for “Guidelines for flood frequency estimation” (NVE, 2009). However, the suggested guidelines do not differ significantly from those of 2002. In general, two kinds of methods are used to estimate design floods: 1) Statistical flood frequency analyses based on historical data, and 2) rainfall-runoff modelling. The exact procedure for the statistical flood frequency analysis depends on the availability of observed river flow data as described in Table NO1. In the case of a gauged site with at least 30 years of daily data, a frequency distribution function is applied directly to the flood series as described in Sections 1.3 and 1.4. In the case of shorter observed series or an ungauged site, the index flood method is applied with the help of longer available series in the area. If no data is available, or if it is otherwise not appropriate, the index flood is derived by regression analysis and regional flood frequency curves (growth curves) are applied (Sections 1.1–1.4). The frequency analysis is based on instantaneous flood data, if sufficiently long series are available. Otherwise, the daily mean values are used and the corresponding instantaneous flood values are estimated by defined regression formulas. All results for gauged and ungauged sites are evaluated subjectively by appropriate experts based on previous results and local knowledge from the area. The estimates are also compared with flood estimates from nearby sites and the values common to a specific region. For the latter regional intervals are given in the suggested guidelines (NVE, 2009).

Table NO1 Procedure for flood frequency analysis according to data availability.

	Data available	**Procedure for calculation of the index flood**	**Procedure for calculation of growth curve for target return periods between Q200 and Q1000**
Gauged: long series	> 50 years		Calculated from 2- or 3-parameter distribution, based on observed series
	30-50 years		Calculated from 2-parameter distribution, based on observed series
Gauged: short series	10-30 years	Calculated from observed series	Calculated by analysis of other long series in the area
	< 10 years	Calculated by correlation with other series and/ or from flood formulas.	Calculated by analysis of other long series in the area
Ungauged		Comparison with nearby sites or calculation from formulas	Use of regional flood frequency curves

1.1 Identification of homogeneous pooling-groups of sites

The pooling of station data is not undertaken in Norway, and in the case of a flood frequency analysis for a station with at least 30 years of data, only at-site data is used. In case fewer than 30 years of data are available at the site of interest, the index flood and/or growth curve are usually calculated from one or several nearby stations with longer observation records (Table NO1). The choice of these stations is mostly made subjectively considering mainly proximity and catchment area as similarity criteria. In the absence of at-site or nearby station data, the index flood and/or growth curve may be calculated from regression formulas. Different regression formulas have been defined for fixed regions (Sælthun, 1997). These flood regions have been defined on the basis of 212 catchments with at least 20 years of observations and no or only little influence by regulations. As it is important to analyse floods generated by different processes separately, the catchments were first separated into four classes according to the season during which the most critical floods in terms of annual flood peak magnitude occur: 1) spring floods during the snow-melt season, 2) summer/autumn floods usually generated by heavy rain, and 3) annual: catchments where the occurrence of critical floods is not constrained to a certain season but may occur during large parts of the year. Catchments along the west coast of Norway typically belong to the annual flood class, whereas both spring and summer/autumn catchments are present in all other parts of Norway. Separate geographical regions were delineated for the three classes based on a hierarchical cluster analysis with six climatic parameters (mean annual precipitation, the relationship between mean annual precipitation and precipitation with a five-year return period (%), mean total number of days with snow cover, mean annual snow depth, mean temperature in January and July). The homogeneity within the identified regions was verified with respect to Wiltshire's homogeneity test. This resulted in two annual regions, four spring flood regions and three summer/autumn flood regions (Figure NO1) as well as a separate glacier region. The latter includes glacier fed catchments with an areal glacier percentage ≥ 5%.

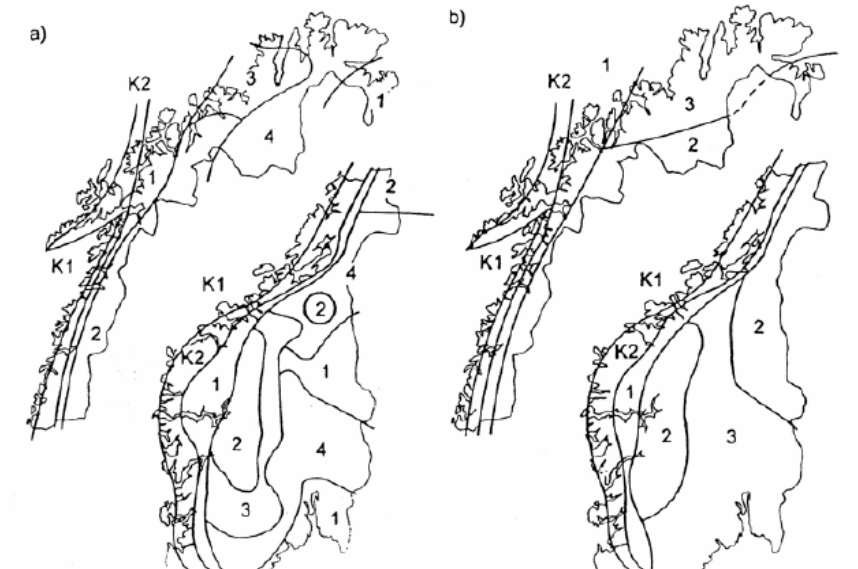

Figure NO1 Flood regions: annual flood (K1 and K2), **(a)** spring and **(b)** summer and autumn (Sælthun, 1997).

1.2 Estimation of the index flood or site-specific scale factor (for regional scale analysis)

Within Norway the mean annual maximum flood is typically used as the index flood. There are two methods of deriving the index flood for a site with short data record or an ungauged site as outlined in Table NO1 and Section 1.1. Firstly, if data are available for a nearby site, these data are used to calculate the index flood by rescaling with catchment area. One or several sites may be used, with either an average value or a value from a particular site adopted. If this is not possible, a regional formula can be used to derive specific values for the index flood. Such regional formulas based on catchment descriptors are available for all flood regions described in Section 1.1 (Table NO2). However, they are only valid for catchments larger than 50 km^2 and should be used with particular caution for catchments smaller than 100 km^2. Specific values for the index flood are translated into flow values for a site by scaling based on catchment area.

Table NO2 Regional formulas for derivation of the index flood (Q_M in l/s/km^2).

Spring flood regions	
1	$\ln Q_M = 0.2722 \bullet \ln S_T - 0.1406 \bullet \ln A_{SE} + 0.1006 \bullet \ln A_{SF} + 0.6172 \bullet \ln Q_N + 2.11$
2	$\ln Q_M = 0.0930 \bullet \ln S_T - 0.0816 \bullet \ln A_{SE} + 0.0281 \bullet \ln A_{SF} + 0.5076 \bullet \ln Q_N + 3.59$
3	$\ln Q_M = 0.3066 \bullet \ln S_T - 0.0220 \bullet \ln A_{SE} + 0.0939 \bullet \ln A_{SF} + 0.3252 \bullet \ln Q_N + 3.09$
4	$\ln Q_M = 0.1848 \bullet \ln S_T - 0.0137 \bullet \ln A_{SE} + 0.0873 \bullet \ln A_{SF} + 0.5143 \bullet \ln Q_N + 2.77$
Autumn flood regions	
1	$\ln Q_M = 1.2805 \bullet \ln Q_N - 0.2267 \bullet \ln(A/L_F) + 0.0664 \bullet A_{SF} + 0.0053 \bullet S_T + 1.00$
2	$\ln Q_M = 1.2910 \bullet \ln Q_N - 0.1602 \bullet \ln(A/L_F) + 0.0508 \bullet A_{SF} + 0.0065 \bullet S_T + 0.65$
3	$\ln Q_M = 1.2014 \bullet \ln Q_N - 0.0819 \bullet \ln(A/L_F) + 0.0268 \bullet A_{SF} + 0.0013 \bullet S_T + 1.07$
Glacier and annual flood regions	
BRE	$\ln Q_M = 0.0119 \bullet Q_N - 0.0848 \bullet A_{SE} + 0.0165 \bullet L_F + 5.81$
K1	$\ln Q_M = 1.5212 \bullet \ln Q_N - 1.1516 \bullet \ln P_N - 0.0569 \bullet A_{SE} - 0.0093 \bullet L_F + 8.80$
K2	$\ln Q_M = 1.1524 \bullet \ln Q_N - 0.0463 \bullet A_{SE} + 1.57$

Where: A = catchment area (km^2), Q_N = mean specific annual runoff (l/s/km^2), P_N = mean annual precipitation (mm), A_{SE} = effective lake (%), A_{SF} = exposed bedrock (%),
L_F = catchment length (km), S_T = gradient of the main river (m/km).

1.3 Choice of a frequency distribution (regional and at-site)

When using observed data, either from the site of interest or from stations nearby, the Green Paper on Guidelines for flood frequency analysis (NVE, 2009) recommends that several different 2- and 3-parameter distributions be compared in each case. The considered distributions include the Log-Normal, Gumbel, General Extreme Value, Gamma, Log-Person, Normal and Pareto distribution. The results using different methods to estimate the parameter values for a distribution are also compared. Parameters are estimated using the method of moments (MOM), probability weighted moments (PWM), and the maximum likelihood method (ML). Usually, the combination of distribution and parameter estimation method resulting in the best fit to the data is chosen. Which of the distributions fits best is decided subjectively by plotting the fitted frequency curves together with the observed data. The observed data is plotted using the Hazen plotting position for the i^{th} ranked (from largest to smallest) flood from a sample of size *n*:

$$\frac{i-0.5}{n}$$

The distributions found to provide the best fit are often either the 2-parameter Gumbel (EV1) or 3-parameter General Extreme Value (GEV) distribution (NVE, 2009). When no or only short observed records are available regional growth curves (see Section 1.4) can be used.

Also for the definition of those several different distributions and parameter estimation methods had been compared. The combination resulting in the best fit was the GEV distribution and PWM to estimate the parameters (Sælthun, 1997).

1.4 Estimation of the frequency distribution (regional and at-site)

When sufficiently long observation records are available for the site of interest, a flood frequency distribution is estimated and selected by comparing several distributions and parameter estimation methods as described above (Section 1.3). In the case of an ungauged site or with only short data records, it is recommended that a regional frequency distribution based on several stations in the area be obtained. Such a regional distribution can be obtained by estimating the frequency distribution for each site separately and combining the at-site estimates (following division by the index flood) to give a regional average. Alternatively, a single flood frequency distribution is sometimes selected for various reasons such as proximity to the site of interest, quality of the flow record or length of record. Finally, the flood frequency distribution derived from nearby sites needs to be scaled to the site of interest. This scaling is typically based on the catchment area, but other factors are sometimes used to derive multiple regression equations. In the absence of long series from stations nearby, the flood frequency distribution is estimated by multiplying a fixed regional growth curve (regional flood frequency curve) with the index flood. Regional growth curves (Figure NO2) have been defined for all Norwegian flood regions shown in Figure NO1 and their definition has been based on the same dataset as the regions (Sælthun, 1997).

	Q_5/Q_M	Q_{10}/Q_M	Q_{20}/Q_M	Q_{50}/Q_M	Q_{100}/Q_M	Q_{200}/Q_M	Q_{500}/Q_M	Q_{1000}/Q_M
H1	1,3	1,6	1,8	2,2	2,5	2,8	3,2	3,5
H2	1,3	1,6	2,0	2,4	2,7	3,0	3,6	3,9
H3	1,3	1,7	2,0	2,6	3,0	3,4	4,2	4,7
K2/ bre	1,2	1,4	1,6	1,9	2,1	2,3	2,5	2,7
K1	1,2	1,4	1,7	2,0	2,2	2,4	2,7	3,0
V1	1,2	1,4	1,6	1,9	2,1	2,3	2,5	2,7
V2	1,2	1,4	1,5	1,7	1,9	2,0	2,2	2,3
V3	1,2	1,4	1,6	1,8	2,0	2,2	2,4	2,5
V4	1,3	1,5	1,8	2,1	2,3	2,6	2,9	3,1

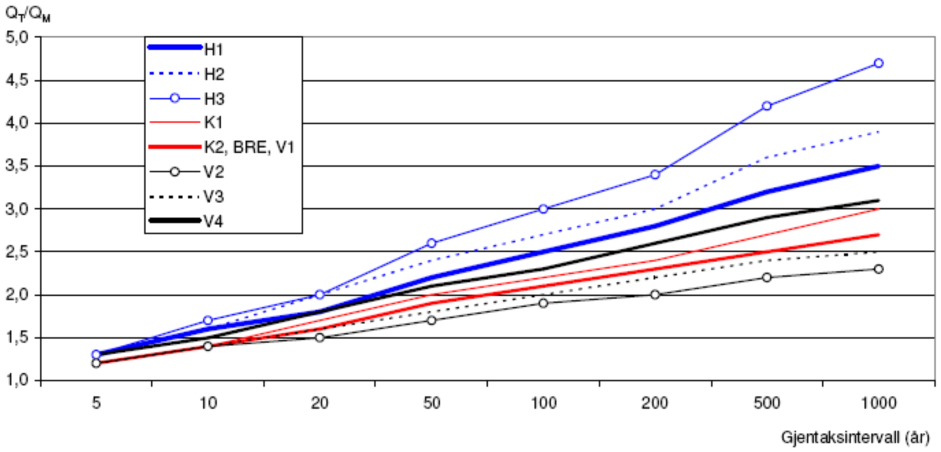

Figure NO2 Regional growth curves (NVE, 2009) for the glacier region (BRE), and the annual (K1, K2), spring (V1-4) and summer/autumn flood (H1-3) regions. In the upper panel the ratios between the flood with return period T Q_T) and the mean flood (Q_M) are given for all regional growth curves, and they are plotted against the return period in the lower panel.

Where the index flood and the growth curve have been calculated using maximum mean daily flow values, instantaneous flood peaks must also be estimated. Where instantaneous flood peak data are available it is recommended that flood frequency analysis of these data is performed. Alternatively, the relationship between the maximum mean daily flow values (Q_d) and the instantaneous flood peak (Q_i) for a site within the catchment or in a comparable catchment can be used. If data are not available, it is recommended that the following formulas be used:

Spring flood: $Q_i / Q_d = 1.72 - 0.17 \bullet \log A - 0.125 \bullet A_{SE}^{0.5}$

Autumn/summer flood: $Q_i / Q_d = 2.29 - 0.29 \bullet \log A - 0.270 \bullet A_{SE}^{0.5}$

However, these regression equations can produce unrealistic values, especially in large catchments and catchments with a high lake percentage. Careful use of these equations is therefore required.

2. Data

2.1 Catchment descriptors

The following catchment descriptors are available. These descriptors have been obtained from maps with a resolution of 1:50,000 and a digital elevation model with a grid size of 25x25m:

- x- and y- coordinates
- elevation
- catchment area
- centre point coordinates
- river gradient[5], 10-to-85%-river-gradient[6]
- river length, catchment length
- hypsographic curve (min, max and 10% intervals)
- precipitation (interpolated from station data or grid points)
- % cover of revervoirs/lakes, glaciers, urban ground, land above the tree line, forest, agricultural land, bogs
- effective lake percentage (this takes account of the location of the lake, and its potential for dampening a flood peak, relative to a downstream point of interest, for example a reservoir)

2.2 Available flood data

The following flood data are available:

- river name, stream gauge name and location (longitude-latitude-altitude)
- catchment area
- record length (only available by downloading the station data)
- time period covered by data (only available by downloading the station data)
- AM and POT series (both can be easily derived from daily flow data)
- instantaneous peak flows (available for many, but not all stations and only since observations were automised – from the 1960s onwards).

Norway is fortunate in having many good quality flood datasets and the Norwegian Water and Energy Directorate (NVE) is keen to supply data for use in the COST Action. Data from Norwegian stations are stored on NVE's Hydra II database. Daily flow data from Norwegian catchments are also held on the European Water Archive as part of the Flow Regimes from International Experimental Network Data project (FRIEND). FRIEND data available to those involved in the FRIEND project for research purposes.

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[5] The river gradient is the difference between the highest river elevation and the lowest river elevation (i.e. station elevation) divided by the river length.

[6] The 10-to-85%-river-gradient is the corresponding elevation gradient between the river points 10 and 85% of its total length away from the station.

3. Discussion

3.1 Purpose and areas of application

The flood frequency analysis procedures described are used to derive flood frequency estimates up to the 1000-year return period. In some circumstances these statistical methods have also been used to derive the PMF (by scaling the 1000 year flood) in large catchments where the rainfall-runoff model used in Norway (PQRUT) is believed to perform less well. The flood estimates are used for the design of hydraulic structures, dam safety assessments and flood-hazard mapping. For flood hazard mapping in Norway, the 200-year flood is the basis for defining inundation zones.

3.2 Main features, merits and drawbacks

The recurrence intervals of interest when using statistical procedures for flood frequency analysis are often 200yr, 500yr and 1000yr. There are several key merits of the approaches detailed which include ease of use, the wealth of experience in applying the procedures and that the procedures make good use of data available for different time resolutions (maximum mean daily flow data and instantaneous flood peaks). The procedures used are applicable to both gauged and ungauged sites, but uncertainty in the estimates can be large. A particular drawback with the approaches detailed is that flood frequency estimates can be based on limited data. For example, just 30 years of annual maxima data from a nearby site can be used to derive a 1000-year flood estimate for a site of interest (Table NO1). In practice, however, the results from several stations are compared, so a flood estimate would never be based on only 30 years of flood data from a single site.

3.3 Recommendations for users

The procedures can be quick to apply, but there is a large degree of subjectivity in an individual flood frequency analysis and users need to consider carefully the impacts of decisions taken. It is recommended that a user compares the resultant flood frequency estimates derived using different stations, frequency distributions and with the results of regional analyses. The regional formulas apply to catchments with areas > 20 km^2, but should be used with caution for catchments with areas < 100 km^2.

4. Case studies

4.1 Examples of practical applications

There are numerous examples of the practical application of these statistical methods for flood frequency analysis within Norway. The procedures are widely used for flood hazard mapping and dam safety assessments.

5. Plans for future development

NVE is currently reviewing the regional equations detailed in Table NO2, with new parameters being considered for inclusion (e.g. catchment area and five-year rainfall). At present, the regional equations do not include catchment area, and it is hoped that by including this parameter the equations can be made applicable for use in smaller catchments (<20km^2). NVE are also reviewing the equations used to estimate instantaneous flood peaks with the aim of developing regional formulas for the calculation of instantaneous flood peaks.

6. References

NVE (2009) Høringsutkast: Retningslinjer for flomberegninger til § i forskrift om sikkerhet ved vassdragsanlegg (Green Paper: Guidelines for flood calculations § regulations relating to the safety of water resource facilities).

Sælthun, N.R. (1997): Regional flomfrekvensanalyse for norske vassdrags [Regional flood frequency analysis for Norwegian catchments]. Rapport 14 / 97, NVE.

PL – Poland (Witold Strupczewski and Bogdan Ozga-Zielinski)

1 Description of method

Methods used in Poland for assessment of design discharge quantiles can be divided in terms of data accessibility into two groups: direct and indirect methods.

Direct methods are applied when the design site coincides with hydrological stations with sufficiently long observation series, or there is a possibility to transpose the results of FFA performed for hydrological stations to that site. Up to the year 2000 these methods used in "at gauged site" FFA were unified by the Ministry Guidelines, which recommended the Pearson type III distribution with parameters estimated by the method of deciles and for special cases by Maximum Likelihood method (Regulations [...], 1969). All other methods were based on the results of FFA performed in accordance with the Guidelines for Flood Frequency Analysis (2005). The ranks of quantiles used to design were specified by other National Guidelines (now updated). After 2000 a new method of FFA was implemented in the Institute of Meteorology and Water Management, which was recommended for use while calculating the design quantiles (Guidelines for Flood Frequency Analysis, 2005). This method adopts a seasonal approach to FFA, as there are in general two main origins of floods in Poland: summer floods caused by rain, and spring, thaw floods. It should be noticed that only the "at-site" part of the FFA was modernized, leaving other methods unchanged. Apart from the indirect methods mentioned above many others remain available (Ciepielowski and Dabkowski, 2006) but their precision cannot be assessed because they have not received sufficient testing.

Indirect methods are recommended for other cases and for ungauged rivers. The consistent system of calculations was elaborated by The Institute of Meteorology and Water Management in the early 1980s, when all possible locations of design site in relation to hydrological network on Polish rivers (e.g. Guidelines for flood frequency analysis, 1998) were covered.

Four cases of location of a design site in respect to the hydrological stations have been identified:

1. The design site coincides with the hydrological station (i.e. catchment area at both sites is the same $A_x=A_w$, where index w corresponds to hydrological station)
2. The design site is located upstream the hydrological station ($A_x<A_W$)
3. The design site is located upstream one hydrological station and downstream another one ($A_u<A_x<A_d$, u – upstream, d-downstream station)
4. The design site is located downstream the hydrological station ($A_x>A_w$)

The transposition of the quantiles $Q_{max\ p}$ to ungauged sites entails reliable results when the area A_x satisfies the condition:

$$0.5\cdot A_w \le A_x < A_w \text{ or } A_w \le A_x < 2\cdot A_w. \tag{PL-1}$$

Then quantiles are calculated from

$$Q_{\max p\, x} = Q_{\max p\, w} \cdot \left(\frac{A_x}{A_w}\right)^n$$

where n is a regional parameter (evaluated for 4 geographical regions and the rank of the quantile).

When the condition in Eq. (PL-1) is not satisfied or the river is ungauged, three methods are proposed depending on the location of the catchment (appropriate a map of applicability of methods):

- Rainfall formula ($A_x<50$ km^2)
- Thaw formula ($A_x\geq50$ km^2)
- Spatial regression equations ($A_x\geq50$ km^2)

Rainfall formula is expressed in the form of equation:

$$Q_{\max p} = f \cdot F_1 \cdot \varphi \cdot H_1 \cdot A \cdot \lambda_p \cdot \delta_J \tag{PL-2}$$

where: f - dimensionless coefficient of typical hydrograph shape, F_1 – maximum module of specific discharge, φ – runoff coefficient for peak flows, H_1 - maximum daily rainfall for probability of excedence 1%; A – catchment area, λ_p – quantile of regional curve $Q_{\max p}/Q_{\max 1\%}$ (for 12 geographical regions), and δ_J – lake reduction factor.

Thaw formula in the form:

$$Q_{\max p} = \frac{aK_0 h_1 A}{(1+A)^{0,2}} \delta_J \delta_B \lambda_p \tag{PL-3}$$

where: h_1 – thaw runoff depth for the probability of excedence 1%, δ_B – swamp reduction factor, K_0 – regional coefficient, and a – correction factor for K_0.

Spatial regression equations

Eq. (PL5) enables evaluation of $Q_{max\,p}$ on the base of catchment's characteristics.

$$Q_{\max p} = \beta_1 A^{0,92} H_1^{1,11} \varphi^{1,07} I_r^{0,10} \psi^{0,35} (1+JEZ)^{-2,11} (1+B)^{-0,47} \lambda_p \tag{PL-4}$$

where β_1 – regional parameter, I_r – river slope, ψ - average slope of the catchment, JEZ – lake index, and B – swamp index.

1.2 Estimation of the index flood or site-specific scale factor

In the form of regional distributions: $\mu_p = Q_{max\,p}/Q_{max\,50\%}$ and λ_p for 5 macro regions divided into 12 regions according to hydrological analysis of regimes and geographical regionalization.

1.3 Choice of a frequency distribution

For at site FFA a distribution is chosen for each season among 4 candidate distributions, namely: Pearson type III (P3), Weibull (WB3), lognormal (LN3) and logPearson (LP3) by means of Akaike information criterion (AIC) and chi-square test.

As it was stated above, the indirect methods have not been updated yet and the P3 distribution for annual maxima is still assumed.

1.4 Estimation of the frequency distribution

The parameters of frequency distribution are estimated using Maximum Likelihood Method.

2. Data

2.1 Catchment descriptors

A set of physio-geographical characteristics used in Rainfall, Thaw and Spatial regression equations (PL-2, PL-3 and PL-4) were developed in the early 1980s, and some of them are presented in The Hydrologic Atlas of Poland, which need to be updated.

There are no current catchment characteristics in the databases except the catchment area and kilometre of river course, 4-scale code for factors affecting runoff and so called "remarks" describing objects that can alter the natural flow at the hydrologic station. The Four-scale code is:

1. N (natural hydrological regime),

2. QN (quasi-natural, there exist some human influences but not important in relation to runoff formation process),
3. Z (regime changed due to the human activity affecting only the time distribution of runoff, not the volume,
4. CZ (regime completely changed in relation to both: time distribution and volume of runoff).

The so called remarks (comments) constitute the short descriptions of factors which can alter the natural flow at the hydrologic station or are important for data verification procedures. The comments show mainly the existence of dams, weirs, water intakes and returns, sewage discharges, water mills, aquatic vegetation influencing the water level etc. upstream or downstream the hydrological station.

2.2 Flood data

There is no a special database for flood data. A central Database contains daily mean stages and discharges, monthly and seasonal peak flows with day and hour of peak.

3. Discussion

3.1 Purpose and areas of application

Design of hydraulic structures, dams, bridges, roads, streets and railways, flood hazard mapping.

3.2 Main features, merits and drawbacks

Recurrence intervals from 20 to 5000 years. Uncertainty of estimated quantiles assessed as one side confidence interval ($1-\alpha = 0{,}84$).

3.3 Recommendations for users

Manuals for users with maps, tables, examples and case studies (in Polish). Seasonal approach – manual with software accepted as the WMO/HOMS component “Guidelines for Flood Frequency Analysis (Long Measurement Series of River Discharge), IMWM, 2005.

5. Plans for future development

Investigation of methods robust enough to model misspecification in respect of upper quantile estimation, a multimodel approach to quantile estimation, a study on the usability of a seasonal approach to flood frequency modelling in Poland, the application of two-shape parameter models in FFA, methods for regional analysis, and the development of new indirect methods for ungauged catchments.

6. References

Ciepielowski A., Dąbkowski S.L. (2006): *Methods for peak flows computation in small catchments*. Projprzem-EKO, Bydgoszcz (in Polish).

Guidelines for computation of bridges’ and culverts’ opening. (in Polish): 1998, Wisła

Guidelines for flood frequency analysis. Long measurement series of river discharge (2005a). Institute of Meteorology and Water Management, Warsaw.

Guidelines for flood frequency analysis long measurement series of river discharge (2005b) WMO/HOMS Component I81.3.01. (http://www.wmo.int/pages/prog/hwrp/homs/Components/English/i81301.htm)

Regulations for computation of the greatest annual discharges for given probability of occurrence to design engineering structures and technical equipment for water management in the field of hydraulic engineering. 1969, Central Office of Water Management, Warsaw (in Polish: ”Przepisy do obliczania rocznych przepływów maksymalnych o określonym okresie powtarzalności. CUGW”).

SK – Slovakia (Ján Szolgay, Silvia Kohnová, Ladislav Gaál)

1. Description of method

Local (at-site) methods

i) Local frequency analysis

At-site estimation of design discharges in Slovakia is based on the technical standard of the Ministry of Environment of the Slovak Republic (OTN ZP, 2003) called "Estimation of *N*-year maximum discharges and *N*-year maximum flood hydrographs for larger catchments". In the technical standard, three theoretical distribution functions (Gamma distribution, 3-parameter lognormal distribution, 3-parameter log-Pearson distribution) and three methods of parameter estimation (method of moments, method of quantiles, maximum likelihood method) are recommended. The plotting positions of annual maxima of peak discharges are usually estimated according to the equation of Chegodayev (OTN ZP, 2003) or Cunnane (DVWK, 1999).

During the years 2005–2007, all design discharges in Slovakia were recalculated using the methodology based on the recommendations of the German Society of Hydraulics and Agricultural Engineering (DVWK, 1999) and the methodology based on L-moments (Hosking and Wallis, 1993).

Regional methods

ii) Regional flood frequency analyses based on envelope curves and regional regression formulae

In the envelope curve methods, an indirect determination of 100-year flood discharges based on the catchment size in geographically contiguous zones (regions). Envelope curves have been applied in several cases to arrive at reliable relationships for practical engineering applications.

Identification of regions has been carried out either subjectively, based on the methodology proposed by Dub (1957) or Halasi-Kun (1968), or according to the catchment boundaries of main rivers in the Czech and Slovak Republic (HP CSSR, 1970).

Regionalisation schemes that are based on different discriminating regionalisation concepts (e.g., catchment geomorphology, boundaries of the catchments of Slovak rivers, etc.) have been tested using the traditional form of the flood formulae in Kohnová (1997) and Kohnová and Szolgay (1995).

The most frequently used regional formula was:

$$q_{100} = \frac{A}{(F+1)^n}(1+\sum_i o_i)\,, \qquad \text{(SK-1)}$$

where q_{100} is the 100-year maximum specific discharge [$m^3s^{-1}km^{-2}$], F is the catchment area [km^2], o_i are correction factors accounting for various catchment shapes, the percentage of forested land, climatic factors, etc., and A, n are regional parameters.

To make the formula (SK-1) flexible and to account better for local runoff-forming conditions different from the common type, diverse multiplicative correction factors (e.g., for the catchment shape, percentage of forested area, presence of lakes and swamps, etc.) have been proposed.

Floods with shorter return periods are derived on the basis of the 100-year discharge estimates Q_{100}, with an inclusion of regional frequency factors:

$$Q_N = a_N . Q_{100}\,,$$

where Q_N is a design flood discharge corresponding to the return period of N years, a_N is a regional frequency factor and Q_{100} is a 100-year design discharge computed from the regional formula in Eq. (SK-1).

A multiple regression method was applied in selected regions of Slovakia to find the formulae for the estimation of selected statistical parameters of maximum discharges. The flood quantiles were estimated by means of the 2-parameter log-normal distribution function and the 2-parameter Extreme Value 1 (Gumbel) distribution function.

iii) Hosking and Wallis methodology

This is the well-described concept of the regional frequency analysis proposed by Hosking and Wallis (1993; 1997, abbr. HW), based on the index flood method (Dalrymple, 1960) and homogeneous pooling groups of sites.

1.1 Identification of homogeneous pooling-groups of sites

Homogeneous pooling groups of sites were delineated according to selected catchment descriptors by means of cluster analysis (using the Euclidean distance metrics and the k-means clustering method).

1.2 Estimation of the index flood or site-specific scale factor

As the index-flood at a given site, the mean of the at-site sample of annual maxima of peak discharges was considered. A stepwise multiple regression was used to determine the relationship between the climatic and physiographic basin characteristics and the index flood values in each pooling group.

1.3 Choice of a frequency distribution

The goodness-of-fit [?best fit] test of Hosking and Wallis (1993) as well as L-moment ratio diagrams were used to select the most appropriate regional distribution function. In most of the pooling groups, the Generalized Extreme Value (GEV) distribution was used to estimate flood quantiles.

1.4 Estimation of the frequency distribution

The frequency distribution was estimated using the regional method based omn the use of L-moments described for instance in Hosking and Wallis (1997).

iv) Region-of-influence method

Unlike in the traditional concepts of a regional frequency analysis, the region of influence (ROI) method (Burn, 1990) makes use of ‘flexible regions’, i.e., for each target site, a unique pooling group is delineated.

1.1 Identification of homogeneous pooling-groups of sites

Homogeneous pooling groups are delineated according to several combinations (pooling schemes) of selected catchment attributes by means of the ROI method, as modified by Gaál and Kyselý (2009).

Once a pooling scheme is defined, the dissimilarity matrix *D* (the Euclidean distance between each pair of sites in the attribute space) is calculated. The size of each pooling group is determined in an iterative way according to (i) the criterion of the regional homogeneity, assessed by the Lu and Stedinger (1992) test, and (ii) the 5*T* rule (Jakob et al., 1999), which suggests using 5 times *T* station-years of data for an estimation of a *T*-year quantile. The iterative procedure of forming the pooling groups is described in detail in Gaál and Kyselý (2009). Once a pooling group is formed, weights based on the dissimilarity matrix *D* are assigned to the sites involved, and all (weighted) data are employed in the estimation of the parameters of the selected distribution function at the given site.

1.2 Estimation of the index flood or site-specific scale factor

As the index flood at a given site, the mean of the at-site sample of annual maxima of peak discharges was considered.

1.3 Choice of a frequency distribution

In all the pooling groups, the GEV distribution was chosen. One of the main reasons for this choice was to preserve the compatibility of the ROI-based flood frequency analysis in Slovakia with the former one, based on fixed homogeneous regions according to the Hosking and Wallis (1993) methodology.

1.4 Estimation of the frequency distribution

The frequency distribution was estimated by means of an adaptation of the the classical index flood method (Dalrymple, 1960, see e.g. Hosking and Wallis, 1997). The uncertainty of the *T*-year quantiles was assessed by means of bootstrap resampling technique (Gaál and Kyselý, 2009).

v) Regional flood frequency analysis with inclusion of extraordinary flood events from ungauged catchments

The methodology described herein is designed to make use of the information on flood extremes that affect ungauged watersheds, and include them in formal flood statistical analyses. The basic concept is to adopt statistical methods developed for temporal data extension, i.e., Markov chain Monte Carlo (MCMC) simulations embedded in a Bayesian framework (Reis and Stedinger, 2005), while the historical flood peaks are replaced by the extremes observed in ungauged catchments. Consequently, (i) the systematic data from a single site are replaced by systematic data from multiple sites within an adequately defined region/pooling group, and (ii) the assumption of stationarity is replaced by the regional homogeneity criterion (Gaume et al., 2010).

1.1 Identification of homogeneous pooling-groups of sites

Homogeneous pooling groups of gauged catchments are identified by means of the heterogeneity measure H1 proposed by Hosking and Wallis (1997). Nevertheless, when ungauged sites are to be included in the regional analysis, an additional condition must be fulfilled. A unique scaling relationship for the index flood must hold for all the watersheds of the pooling group. Furthermore, it is also important that the defined homogeneous pooling groups have a consistency from a physiographic and geographic point of view. Otherwise, it is not possible to classify the ungauged sites in the identified pooling groups.

1.2 Estimation of the index flood or site-specific scale factor

In order to estimate the index flood for ungauged sites, a rather simple regression model

$$\mu_i = cA_i^{\beta}$$

is used, where μ_i (A_i) is the index flood (catchment area) at site *i*, and *c* and *β* are the coefficients to be found by the regression. Note that a generalization to more complex relations is trivial.

In order to delineate homogeneous pooling groups and adjust index flood relations, the sample means (or medians) of the discharge series are plotted against the watershed areas (in log-log scales) and a straight line in the cloud of points is fitted. A measure of the uncertainty of this fit is then obtained based on a modified version of the Wilcoxon-Mann-Whitney test, the concept of which is described in detail in Gaume et al. (2010).

1.3 Choice of a frequency distribution

For modelling the joint probability distribution of the pooled sample of systematic gauged annual peak discharges and the samples available at the ungauged sites, the GEV distribution is employed.

1.4 Estimation of the frequency distribution

The crucial part of the presented method is the way the likelihood function is formulated, since it has to reflect the strategy how the ungauged extremes were sampled (Gaume et al., 2010).

Numerically, the Bayesian MCMC simulations are adopted for an estimation of the frequency distribution since (i) they can handle different sources of hydrological information (systematic and non-systematic observations), (ii) they can account for uncertainties in the measurements of the hydrologic extremes, and (iii) also provide estimates of confidence bounds for the estimated quantiles.

2. Data

2.1 Catchment descriptors

In the process of identification of regions and homogeneous pooling groups, different climatic and physiographic catchment attributes were used, which were derived either from various digitized maps or a DEM of Slovakia:

- catchment area [km^2],
- gauge datum [m a.B.],
- length of the river network [km],
- mean catchment elevation [m a.s.l.],
- percentage of forested area [%],
- long-term (1931–1980) mean annual precipitation [mm],
- long-term mean annual runoff [l.s^{-1}.km^{-2}],
- 2, 50 and 100-year return values of the maximum daily precipitation amounts [mm].

2.2 Flood data

Local (at-site) methods

- annual maximum discharges from all gauging stations in Slovakia;
    - record lengths: approx. from 15 to 108 years;
    - time span covered: 1901–20011;
- validation and accessibility of data: Slovak Hydrometeorological Institute.

Regional methods

- seasonal maximum discharges from summer / winter seasons;
- annual maximum discharges
    - catchment area: from 20 to 400 km^2
    - record lengths: from 15 to 60 years;

    - time span covered: 1921–2003;
- validation and accessibility of data: Slovak Hydrometeorological Institute.

3. Discussion

3.1 Purpose and areas of application

Local (at-site) methods

Methods of local frequency analysis are aimed at estimating 100-year quantiles of maximum discharges for design of hydraulic structures – dams, urban hydrology and flood-hazard mapping in gauged sites, i.e., in places with direct observation. When the site of interest is located between two gauging stations, in simple cases the following approach, based on mathematical interpolation method, is used:

$$Q_N^o = Q_N^h + \frac{Q_N^d - Q_N^h}{A^d - A^h}.\left(A^o - A^h\right)$$

where Q_N^o (Q_N^h, Q_N^d) is *N*-year quantile of maximum discharge in the target (upper, lower) station, and A^o (A^h, A^d) is the catchment area in the target (upper, lower) station. Furthermore, it is also possible to apply graphical methods for the estimation of flood quantiles in ungauged catchments. For this purposes, flood routing procedures such as the Kalinin-Miljukov method, the cascade of nonlinear reservoirs or hydraulic modelling is recommended (OTN ZP, 2003).

Regional methods

The envelope curves are used mostly for estimation of 100-year quantiles of maximum discharges for design of hydraulic structures in places with no direct observations. The regional regression formulae are used for estimation of quantiles of maximum discharges for design of hydraulic structures in places without direct observations, especially for the High Core Mountain region, Volcanic Mountain region and Flysh region of Slovakia.

The HW and the ROI methods can be used for flood hazard mapping and engineering design of hydro-technical constructions for the whole territory of Slovakia. The HW method can handle both gauged and ungauged sites, while in the ROI method, further studies are needed to extend the applicability of the method for ungauged cases.

3.2 Main features, merits and drawbacks

The envelope curve approach has been used by the Slovak Hydrometeorological Institute since 1954 for a regional estimation of design discharges for the catchment areas larger than 20 km^2.

In the studies of Kohnová and Szolgay (1995; 1996), a comparison of design floods estimated by the traditional regional formulae with statistically derived 100-year floods based on new hydrometric data of annual floods from 261 small and mid-sized catchments was discussed. The comparison has shown that the most popular formula (Eq. SK1) of Dub (1957) can be regarded as an envelope curve to the statistically derived values in almost all regions.

The regional regression formulae are recommended for practical application mostly in cases when design discharges with shorter return periods (1 to 20 years) are required, especially at ungauged sites in the high Core Mountain region, Volcanic Mountain region and Flysh region of Slovakia.

To make the HW approach applicable to ungauged catchments throughout Slovakia, maps of pooling groups for summer, winter and annual floods were constructed. In all homogenous pooling groups, the regional growth curves and the index flood formulae were derived. For the pooling of L-moment characteristics, also contour maps of L-coefficient of variation, L-skewness and L-kurtosis for annual, summer and winter maxima of discharges were constructed.

In comparison with statistically estimated flood quantiles, the HW method results both in overestimated and underestimated flood quantiles. This fact makes return-period based risk analysis difficult, since the “actual return-periods” remain uncertain. The degree of design safety associated with this (and similar) methods would be acceptable, if using a large independent flood dataset (or simulation) it could be shown, that some measure of over- and underestimation is comparable with the uncertainty associated with statistical methods, when used under average engineering design conditions (record length, data homogeneity, data quality, uncertainty resulting from the choice of the distribution function and the parameter estimation method, etc.).

In general, none of the methods of regional flood frequency analysis developed during the past decades in Slovakia assessed the uncertainty of the estimated flood quantiles although it is a standard requirement in frequency studies generally. Recently, in parallel with revisiting the HW approach, the ROI method was developed in the geographical settings of Slovakia. One of the merits of these steps is the fact that the recently built program code also allows for deriving confidence intervals for the flood quantiles in a straightforward way, using bootstrap resampling. Beyond this, further studies are necessary to examine the performance of the ROI pooling methodology in comparison with the HW method. For instance, a number of new ROI pooling schemes could be constructed based on a combination of an extended number of catchment attributes, and/or the relative importance of the site attributes in the individual pooling schemes could be defined.

4. Case studies

Examples of practical applications of regional flood frequency analysis in Slovakia are presented in the following studies:

Gaál, L., Kohnová, S., Szolgay, J., 2010. Revisiting regional flood frequency analysis in Slovakia: the region-of-influence method vs. traditional regional approaches. Geophysical Research Abstracts, Vol. 12, EGU2010-13693-2. European Geosciences Union, General Assembly 2010, 2–7 May 2010, Vienna, Austria.

Gaume, E., Gaál, L., Viglione, A., Szolgay, J., Kohnová, S., Blöschl., G., 2010. Bayesian MCMC approach to regional flood frequency analyses involving extraordinary flood events on ungauged sites. *Journal of Hydrology* 394(1-2): 101–107. doi:10.1016/j.jhydrol.2010.01.008.

Kohnová, S., Szolgay, J., Solín, L., Hlavčová, K., 2006. *Regional methods for prediction in ungauged basins*. Key Publishing, Ostrava. 113 pp.

Kohnová, S., Szolgay, J., Hlavčová, K., 2008. Regional flood frequency analysis of annual maximum floods from the winter season in Slovakia. *Meteorological Journal* 11(1-2): 65–70.

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Kohnová, S., Szolgay, J., 2000. Identification of homogeneous pooling groups for regional assessment of design discharges. In: *Hladný, J. et al. [Eds.]: Hydrology Days 2000 – New Impulses and Visions for the Next Century*. ČVH, SVH, ČHMÚ, Plzeň, Czech Republic. 291–298. [in Slovak]

Kyselý, J., Gaál, L., Picek, J., 2010. Comparison of regional and at-site approaches to modelling probabilities of heavy precipitation. *International Journal of Climatology* [in press]. doi:10.1002/joc.2182.

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5. Plans for future development

The preliminary results of the intercomparison of the HW and ROI methods for flood frequency analysis in Slovakia were presented in (Gaál et al., 2010).

Further studies are needed to extend the applicability of the ROI method for ungauged cases.

The MCMC-based of regional frequency analysis with the main focus on an inclusion of extraordinary flood events that affected ungauged catchments.

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SL – Slovenia (Mira Kobold, Mitja Brilly and Mojca Šraj)

1. Description of method

1.1 Identification of homogeneous pooling-groups of sites

Regional flood frequency analysis and identification of homogeneous pooling-groups have not yet been carried out in Slovenia. More types of flow regimes were identified in Slovenia (Figure SL-1) according to the characteristic landscape unit and to the water source.

1.2 Estimation of the index flood or site-specific scale factor

No special scale factor is calculated.

1.3 Choice of a frequency distribution

At the moment the return period of the extreme events is estimated upon frequency analyses of peak discharges as univariate statistical approach in Slovenia. The traditionally used flood frequency distributions in Slovenia are the Pearson type 3 and log-Pearson type 3. Some other distributions such as Gumbel distribution and Log-Normal have been tested in case studies at-site locations. Univariate approach can sometimes lead to underestimation of the risk associated to a given event. Therefore Faculty of Civil and Geodetic Engineering at the University of Ljubljana is currently running the national research project where multivariate statistical approach with the use of Copula functions is examined (Brilly and Šraj, 2011).

1.4 Estimation of the frequency distribution

Flood frequency analysis is performed with annual maximum discharges for at-site observations. Hydrological service at Slovenian Environment Agency uses its own program DIST which fit five different distributions (Normal, log-Normal, Pearson type 3, log-Pearson type 3 and Gumbel distribution) to the at-site observed series. The estimation tests were used to determine which distribution is the most appropriate. The maximum absolute deviation of theoretical values from empirical ones is determined for each theoretical distribution, and the Smirnov-Kolmogorov test and Chi-square test are calculated.

Widely used in Slovenia is also the HEC-SSP statistical software package developed by US Army Corps of Engineers for performing the statistical analyses of hydrological data.

Flood frequency statistics with different return periods were calculated for the all sites of gauge location with at least 20 years of observations. For sites where no or little observations are available, data from the nearby stations or reference catchments with similar hydrological properties are used to estimate the design flood.

2. Data

2.1 Catchment descriptors

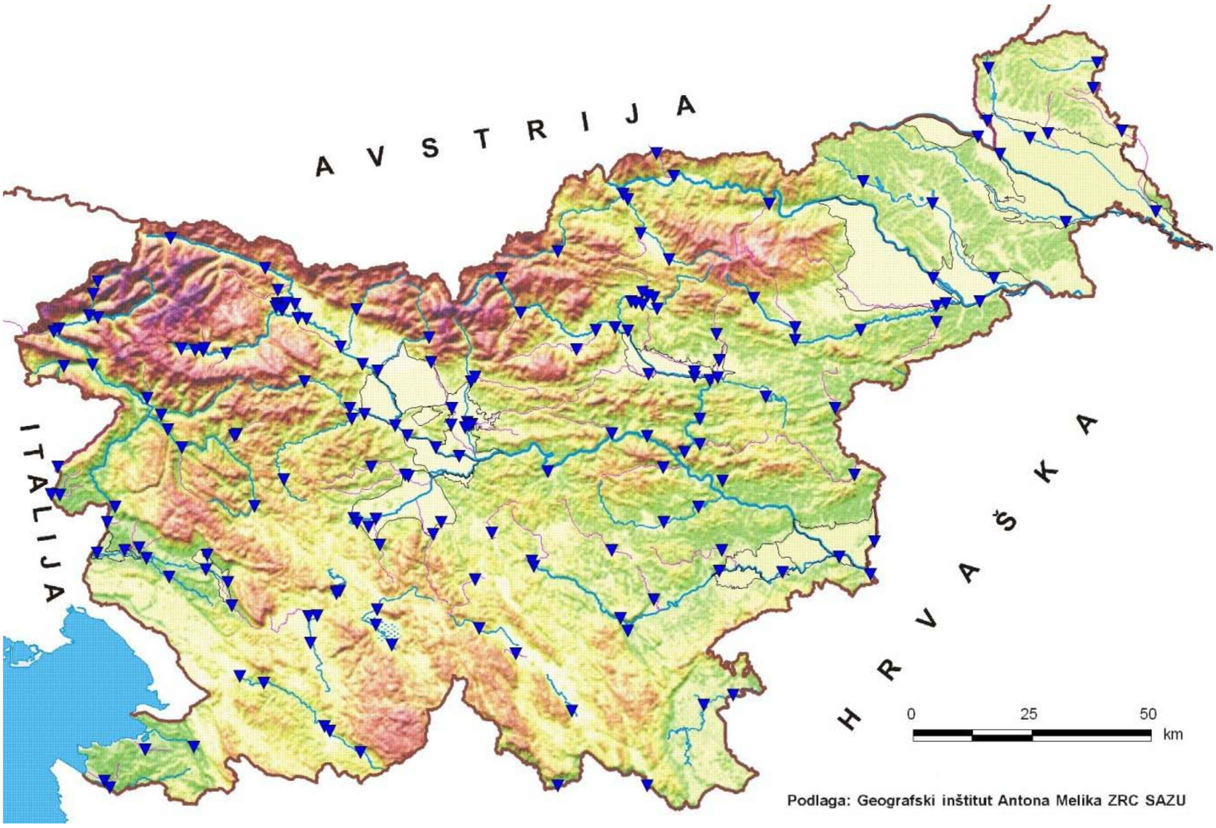
The catchment descriptors are characteristics representing the parameters of water gauging stations: national code of a water gauging station, type of measurement method, name of the place where a gauging station operates, name of the stream on which a gauging station is located, drainage area, distance of the gauging station cross-section from the river mouth or from the state border, the "zero" point of the staff gauge altitude (in metres above the level of the Adriatic), Gauss-Krueger and geographic coordinates of the location of the gauging station, beginning of observations. These descriptors are reported in Hydrological Yearbook of Slovenia available at http://www.arso.gov.si/vode/publikacije in poročila/letopisi.html.

Data sources such as digital elevation model, stream network, lakes, land cover, geology, hydrogeology, soils, depth to ground-water table, precipitation records are also available.

2.2 Flood data

The Slovenian Environment Agency takes care for national hydrological data archive. Most of the data derived from the measurements within the national hydrology network are processed in the information system of the national hydrology service named HIDROLOG. Data archive includes hourly and daily data of water-level and discharge, data of water temperature and concentration of suspended material, and hydrometric measurements. Tables of extremes include daily and monthly instantaneous minimums and maximums of hydrological quantities from which the annual minima and maxima are determined.

Throughout history in the territory of Slovenia, the system of hydrological observations and measurements and the number of water gauging stations on surface waters has changed and been adapted to the existing needs and developments of the measuring equipment. The first measurements in the territory of Slovenia extend from the second half of the 19th century in the period of the Austro-Hungarian monarchy. The highest number of operating stations was in the first half of 1970s. The development of the hydrological network was influenced in particular by the protection of settlements against floods and the use of water for energy, technological and water supply purposes, and nowadays increasingly more by the needs to study and protect the environment. In the 1980s, many water gauging stations were terminated. The main reasons were different, ranging from maintenance cost reduction, the end of the planned period of operation to unsuitable microlocation etc. In the past few years, the number of surface water hydrological monitoring gauging stations remained almost the same. It the territory of Slovenia with surface area of 20,273 square kilometres are 185 gauging stations on water courses and 17 gauging stations on karstic springs.



Podlaga: Geografski inštitut Antona Melika ZRC SAZU

Figure SL1 Map of existing gauging stations in Slovenia

The hydrological data are the basis of monitoring the hydrological situation, forecasting and informing the relevant authorities in an emergency situation as well as for natural disasters and accidents caused by human factors. Furthermore, they are the basis for preparing a water balance, an assessment of water sources, assessment of hydrological elements of ecological status of waters and, increasingly in the last number of years, a support to prediction models in the form of basic input data. All archive daily data as well monthly and yearly values as well the real time data can be simply accessible through the website http://www.arso.gov.si/vode/podatki/.

3. Discussion

3.1 Purpose and areas of application

The main areas of flood frequency analysis are flood hazard and risk mapping, design of structures, reservoirs, dikes, technical flood protection solutions, etc.

3.2 Merits and drawbacks

The main focus of interest is floods with any recurrence interval. Uncertainty of the flood estimates and lack of regionalization methods are drawbacks in Slovenia.

4. Case studies

Experimental watersheds are critical to the advancement of hydrological science. By setting up three experimental watersheds, Slovenia obtained its grounds for scientific research, further development of the science and discipline and at the same time provided support to the teaching and studying process (Šraj et al., 2008b). Watersheds have been equipped with modern measuring equipment for precise measurements of precipitation, intercepted precipitation, discharges, erosion and water quality. Measurements and analysis on the experimental watersheds improved the current understanding of hydrological processes.

Three experimental watersheds were set up. The Dragonja river experimental watershed, where research is focused on the influence of afforestation of the watershed in a Mediterranean climate (Globevnik and Brilly, 2003; Petkovšek and Mikoš, 2004; Šraj et al., 2008a), the Reka river watershed in a partly karstic area (Brilly et al., 2002), and the Glinščica river watershed, where the implications of the urban environment are studied (Brilly et al., 2006; Šraj et al., 2010).

Hydrologic modelling is very common for the determination of design discharges in practice, especially by ungauged basins. For a given recurrence interval a synthetic storm with the use of rainfall intensity-duration-frequency curves is generated. The influence of synthetic hyetographs on modelled runoff hydrograph was investigated for the Glinščica river (Šraj et al., 2010). The rainfall-runoff process is difficult to simulate precisely. Models usually use the concept of the effective rainfall where rainfall hyetograph is divided into losses and effective part. The effective rainfall is then used as the model input to provide runoff hydrograph. Accurate representation of the precipitation excess is essential for rainfall-runoff models. Also the influence of rainfall intensity distribution and the maximum rainfall intensity position of synthetic hyetographs of different probability and duration were evaluated. The study showed that the maximum rainfall position of the synthetic hyetograph has essential influence on runoff hydrograph, especially on time-to-peak. With the increasing of the rainfall duration the differences in time-to-peak increase considerable. Also rainfall pattern distribution has a great impact on runoff hydrograph. Constant rainfall intensity distribution produces essentially lower peaks than typical temporal rainfall distribution, especially by longer rainfall durations. Results of the model clearly refer to the importance of the excess hyetograph on runoff prediction. The influence is evident in peak discharge, time-to-peak and volume of the runoff hydrograph.

5. Plans for future development

Monitoring

Several gauging sites were modernised in last few years to improve observation and data access. The number of automatic stations is growing every year and the data is available to the public on the Slovenian Environment Agency's website with a short time delay. The upgrading and modernisation of the network of gauging stations for groundwater, surface water, meteorological stations and radar by 2015 has been projected within the project "Upgrading the system for monitoring and analysing the state of the water environment in Slovenia", financed by the EU Cohesion Fund and through the resources of the Republic of Slovenia. The primary objective of the project is to provide reliable, high quality and spatially representative meteorological and hydrological measurements, which will enable comprehensive monitoring and analysing of the water environment conditions in Slovenia and more accurate forecasts of extreme hydrological events. The entire project is focused on reduction of the potential harmful impact of water and establishing sustainable development of the water environment at a national level.

Flood frequency analyses improvements

Since univariate approach can sometimes lead to underestimation of the risk associated to a given event, Faculty of Civil and Geodetic Engineering at the University of Ljubljana is currently running the national research project where multivariate statistical approach with the use of Copula functions is examined (Brilly and Šraj, 2011). Complex hydrological events such as floods always appear as the consequence of few correlated random variables (peak, volume, duration, etc.). Therefore single-variable frequeny analysis can only provide limited assesment of these events. As an example, an event with a peak of a 100-years return period could be less damaging than an event with a 10-years return period both in peak and volume. To fully understand all three variables and their relationship a multivariate statistical approach is necessary. Development of new approach and its application is still progress at that moment. There are still open questions about the choice of samples, metodologies and results analyses.

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SP – Spain (Luis Mediero and Luis Garrote)

1. Description of method

The Centre for Hydrographic Studies of CEDEX developed a set of procedures for flood frequency analysis (CEDEX, Jimenez et al.) based on a regionalisation study of Spanish hydrological basins conducted using the L-moments methodology proposed by Hosking and Wallis (1997).

The results of the regional study were extended to larger ungauged basins by a multiple regression method from the climatic and physiographic catchment descriptors. A modification of the rational method is used in sites with smaller basins areas, where discharge gauge stations exist only rarely. This hydrometeorological method was proposed to take advantage of the higher resolution of precipitation gauge stations network. As there is a lack of discharge data in these basins, the method takes as input the local frequency curve of annual maximum daily precipitation, which is estimated from observed data.

Flood frequency analyses in Spain are based on Annual Maximum Series (AMS) of discharge recorded at gauge stations. Spain is divided into 36 homogeneous regions by means of geography. Flood frequency curves are estimated by a Generalised Extreme Value distribution (GEV), Gumbel (G) and Two Components Extreme Value distribution (TCEV), which are fitted by the Probabilistic Weighted Moments (PWM) method. A regional procedure based on the regional shape parameter method is used, which uses a regional value of the L-coefficient of skewness (L-CS) and local values of the mean an the L-coefficient of variation (L-CV). Regional values of L-CS are provided in each homogeneous region.

At ungauged sites, peak flows are estimated by flood quantiles to known climatic and physiographic characteristics, usually the basin area, mean elevation and precipitation quantiles, through regression models.

1.1 Identification of homogeneous pooling-groups of sites

Spanish geography shows a high climatic variability caused by its abrupt orographic conditions, e.g. in the Ebro River basin, elevations range from 0 m.o.s.l. in the Ebro delta to 3.404 m.o.s.l in the Aneto peak, mean annual rainfall ranges from 450 mm to 2500 mm and 100-year maximum daily rainfall ranges from 80 mm to 160 mm.

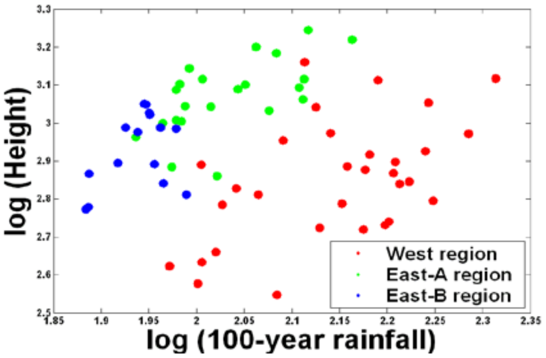


Figure SP1 Elevation and 100-year daily maximum precipitation in the three homogeneous regions of the Tagus basin.

This fact led to the identification of geographical regions based on homogeneity of climatic and physiographic conditions as precipitation quantiles and elevation (Figure SP1). Homogeneity in each identified region was tested by the heterogeneity measures of Hosking and Wallis (1993). The resulting 36 regions are shown in Figure SP2.

Figure SP2: Homogeneous regions in Spain.

1.2 Estimation of the index flood or site-specific scale factor

The index-flood method is a commonly used regional method, supplying regional values of L-CS and L-CV in a homogeneous region. However, the relationship between L-CV and basin area is complex as it depends on the interaction between different runoff processes and it has been observed that L-CV increases with basin area, until a threshold, and then decreases with basin area (Blöschl and Sivalapan, 1997; Iacobellis et al., 2002). As this L-CV pattern has also been observed in Spanish regions, a regional shape estimation procedure was selected to relax the restriction of a regional value of L-CV. Flood frequency curves are estimated in each station by a regional method based on a regional shape parameter procedure, which uses a regional value of L-CS and local values of mean and L-CV (Lettenmaier et al., 1987). Regional values of the L-CS are provided in each region.

1.3 Choice of a frequency distribution

A frequency distribution was selected in each region (Table SP1), taking into account its fit to the observed data, the estimation robustness for higher return periods and the description of the observed data statistical properties in the whole homogeneous region (Mediero and Jimenez, 2008). The Generalized Extreme Value (GEV) distribution was found to be the most suitable distribution in most regions:

$$F(x) = exp\left\{-\left[1 - k\left(\frac{x-u}{\alpha}\right)\right]^{\frac{1}{k}}\right\}$$

The Gumbel function was selected in regions with milder climatic conditions:

$$F(x) = exp\left\{-exp\left[-\left(\frac{x-u}{\alpha}\right)\right]\right\}$$

The Two Component Extreme Value (TCEV) distribution, which is the product of two Gumbel distributions, was selected in Mediterranean regions, where there are two types of rainfall events caused by different meteorological conditions: frontal storms and heavy convective storms. The former are the more frequent events and are described by the first Gumbel distribution. The latter are less frequent, but much higher, and are described by the second Gumbel distribution.

$$F(x) = \exp\left[-e^{-\frac{x-u_1}{\alpha_1}} - e^{-\frac{x-u_2}{\alpha_2}}\right]$$

Table SP1 Frequency distributions selected in each homogeneous region.

Region	Function	Region	Function
11	GEV	53	GEV
12	GEV	54	GEV
13	GEV	61	GEV
21	Gumbel	71	GEV
22	GEV	72	TCEV
23	Gumbel	73	GEV - TCEV
24	GEV	81	GEV
25	GEV	82	TCEV
26	GEV	83	GEV
31	GEV	84	TGEV
32	GEV	91	GEV
33	GEV	92	GEV
34	GEV	93	GEV
41	GEV	94	GEV
42	GEV	95	GEV
43	GEV	96	Gumbel-GEV
51	GEV	101	GEV
52	GEV	102	GEV

1.4 Estimation of the frequency distribution

Moments (MOM), Probability Weighted Moments (PWM) and Maximum Likelihood (ML) methods were compared. PWM is more reliable for estimations from skewed distributions as flood data (Greenwood et al., 1979; Hosking and Wallis, 1997) and ML shows a high variability of higher return quantiles estimation. As a result, the PWM method was selected. Historical data were used where available. First, the historical period, the number of peaks exceeding a threshold in that period and the length of systematic record are identified. A modification of the PWM method is used, which is based on a weighting factor similar to that used with the MOM method (Stedinger and Cohn, 1986). The use of historical data improved the estimation in some sites (Figure SP3) and the regional value of the L-CS was modified from these results in some regions, like the 92th region.

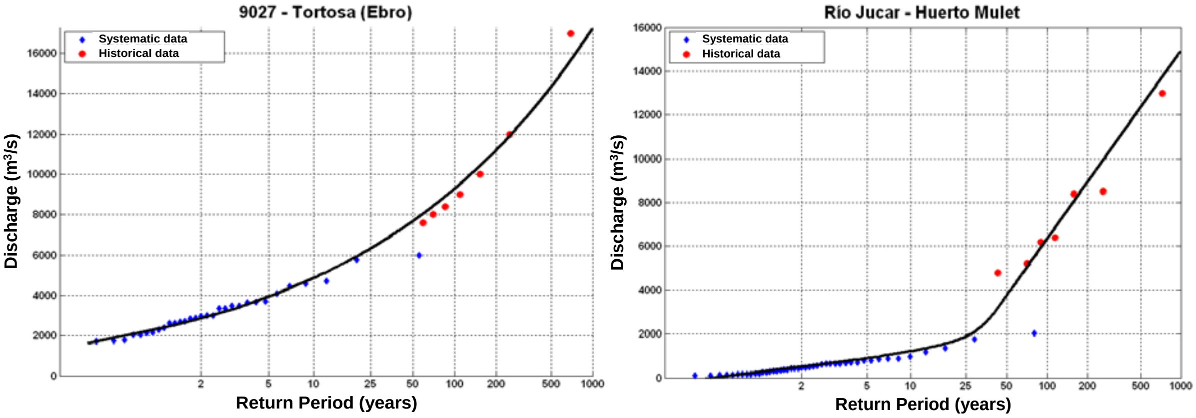


Figure SP3 Examples of flood frequency curves with historical data.

For the estimations at ungauged sites, multiple regression equations were fitted in each region for 2, 5, 10, 25, 100 and 500 years of return period (Mediero and Jimenez, 2007). A multiple regression equation provides the relation between the flood flow (Q_T) and a set of explanatory variables (X_i), which are the climatic and physiographic characteristics of the basin (Stedinger and Tasker, 1985):

$$Q_T = 10^{b_0} \cdot X_1^{b_1} \cdot X_2^{b_2} \cdot \ldots \cdot X_n^{b_n}$$

A statistical analysis was carried out in each region to identify the variables that best explain the flood flow for a given return period, by means of the Mallow's coefficient, the determination coefficient and the correlation between variables. A strong relationship between flood flow and basin area was found in the logarithmic space. Other explanatory variables were the annual maximum daily precipitation for a given return period, the mean basin elevation and the initial abstraction. The regression equations fitted in the 22th region are shown in the Table SP2 as an example.

Table SP2 Regression equations in the 22th region. Q_T is the flood flow for the T-year return period, A is the basin area in km^2, P_T is the annual maximum daily precipitation for the T-year return period, R^2_{corr} is the adjusted coefficient of determination and e is the standard error of prediction.

$Q_2 = 10^{-20.0285} A^{0.7844} P_2^{12.4275}$	$R^2_{corr} = 0.98$	$e = 25\%$
$Q_5 = 10^{-23.1685} A^{0.6481} P_5^{13.9405}$	$R^2_{corr} = 0.96$	$e = 20\%$
$Q_{10} = 10^{-20.0814} A^{0.6364} P_{10}^{11.6693}$	$R^2_{corr} = 0.96$	$e = 17\%$
$Q_{25} = 10^{-18.1705} A^{0.6698} P_{25}^{10.1204}$	$R^2_{corr} = 0.93$	$e = 21\%$
$Q_{100} = 10^{-14.7762} A^{0.7238} P_{100}^{7.7968}$	$R^2_{corr} = 0.87$	$e = 27\%$
$Q_{500} = 10^{-13.3324} A^{0.7662} P_{500}^{6.728}$	$R^2_{corr} = 0.81$	$e = 30\%$

Flood estimation in smaller basins is usually hampered by a lack of observed flow data. The regional procedures for estimating the peak discharge presented here are generally not recommended for use in these basins as the runoff concentration process has a strong dependence on physical and rainfall characteristics not captured in the available calibration dataset. In these small basins, design peak discharges for a given return period (Q_T) are estimated by a modified rational method, which was developed in Spain by Témez, (1991). This method takes advantage of the availability of precipitation data:

$$Q_T = \frac{C \cdot I_t \cdot A}{3.6} \cdot K$$

where C is the runoff coefficient, I (mm/h) is the rainfall intensity, A (km^2) is the basin area and K is the uniformity coefficient, which takes into account the runoff evolution in time during the storm duration.The runoff coefficient (C) is calculated from the maximum daily rainfall for the given return period (P_d) and the initial abstraction of the Curve Number method (P_0).

$$C = \frac{(P_d - P_0)(P_d + 23 \cdot P_0)}{(P_d + 11 \cdot P_0)^2}$$

The rainfall intensity is calculated as the maximum mean rainfall intensity (I_t) for a storm duration equal to the time of concentration (t):

$$I_t = I_d \cdot \left(\frac{I_1}{I_d}\right)^{\frac{28^{0.1} - t^{0.1}}{28^{0.1} - 1}}$$

where I_d is the mean daily rainfall intensity, calculated from the maximum daily precipitation and (I_1/I_d) is a coefficient that relates the mean rainfall intensity in one hour to the mean rainfall intensity in one day.

The maximum daily rainfall for a given return period (P_d) is calculated from the observed maximum daily precipitation series recorded in the basin. A SQRT-ETmax distribution function is fitted to the annual maximum daily rainfall series:

$$F(x) = \exp\left[-k \cdot \left(1 + \sqrt{\alpha \cdot x}\right) \cdot \exp\left(-\sqrt{\alpha \cdot x}\right)\right]$$

2. Data

2.1 Catchment descriptors

The regional study was carried out over the following basin parameters: Gauge longitude and latitude, basin area, T-year daily maximum and annual mean rainfall, maximum, minimum and mean elevation, basin and river slope, river length, potential maximum retention, infiltration rate, time of concentration and impervious portion of the basin area. These parameters were obtained from a set of raster maps with a grid size of 500 m.

2.2 Flood data

The source of flood data in Spain is the Centre for Hydrographic Studies of CEDEX. These data are available in: http://hercules.cedex.es/anuarioaforos/default.asp

Streamflow data used for flood frequency analysis are AMS of instantaneous peak flows recorded in gauge stations with a length higher than 20 years. Some stations have only AMS of daily mean flows, which must be transformed into instantaneous peak flows by the formulae derived from Fill and Steiner (2003). Trends and shifts are detected by the following techniques: (1) identification of outliers by the U.S. Water Resources Council method (USWRC, 1981); (2) a graphical analysis is carried out at a local scale by plotting the cumulative AMD in each station; (3) a more robust analysis is carried out in each station by the Mann-Kendall test; (4) the discordance measure of Hosking and Wallis (1997) is computed at a regional scale to identify stations that are grossly discordant with the group as a whole; (5) further investigation is carried out over the stations with possible trends from the results of the previous four analyses.

PDS are also available, but were not used in the regional analysis. A seasonal analysis is currently being carried out with these PDS.

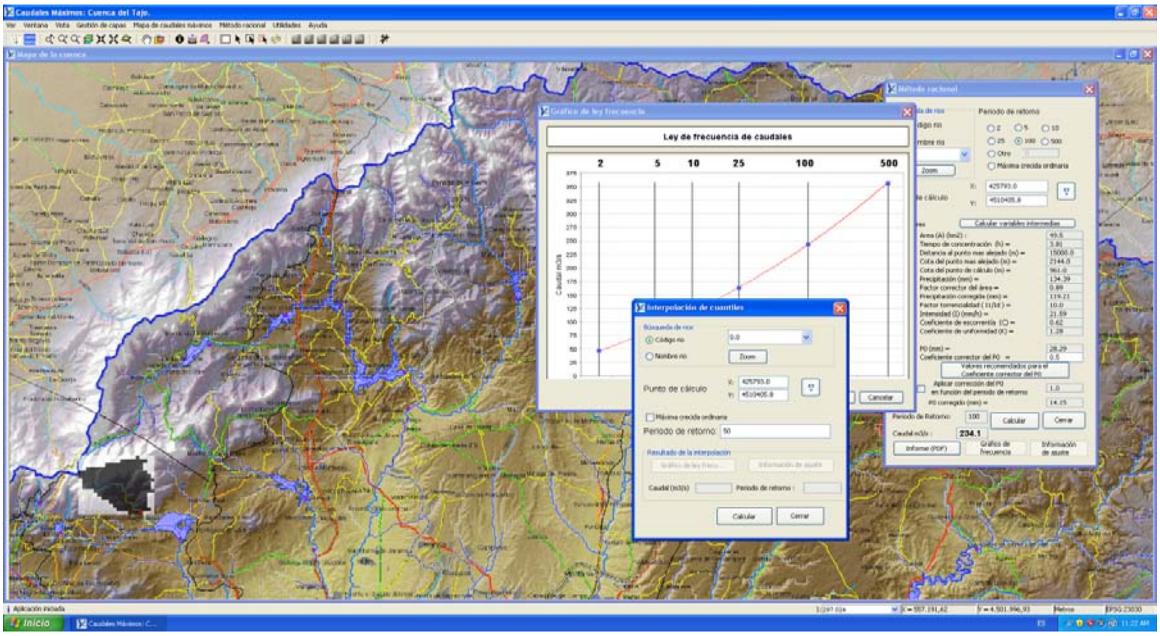
3. Discussion

3.1 Purpose and areas of application

This methodology has been applied to the development of the "map of peak flows"(Jimenez-Alvarez and Mediero, 2009; Garcia-Montañes et al., 2008), which consist of a series of raster maps that give the instantaneous peak flow for a given return period (2, 5, 10, 25, 100 and 500 years), in each cell of the river network of Spain with basin areas greater than 50 km^2. For smaller basins, a software tool based on the modified rational method is supplied, but its parameters must be defined by the user (Figure SP4).

The main use of this map is the flood-hazard mapping following the Directive 2007/60/EC on the assessment and management of flood risks, by coupling the map with a hydraulic model. Other uses are the design of hydraulic structures like bridges and culverts. Dams require a more specific and detailed hydrological study, which is based on a multivariate flood frequency analysis methodology.

The map of peak flows tool is available in: http://www.marm.es/es/agua/temas/gestion-de-los-riesgos-de-inundacion/snczi/mapa-de-caudales-maximos/



Punto de cálculo X: 425793.0 Y: 4510405.8

Período de retorno: 50

Período de Retorno: 100

Caudal m3/s: 234.1

Figure SP4 Capture of the map of peak flows software tool.

3.2 Main features, merits and drawbacks

This methodology has been a breakthrough in the hydrological field in Spain, as it is the first attempt to develop a general method to estimate the quantiles of the peak flow frequency distribution at a regional scale. This analysis over all AMD series recorded in Spain will make further improvements and studies easier. As well, the "map of peak flows" is an extension of the regional study on observed data to ungauged sites, providing the peak flows for different return periods in the whole area of Spain for basin areas greater than 50 km^2.

The "map of peak flows" is very recent and drawbacks will be known in the future.

Uncertainty of the quantile estimation by the PWM method and the shape parameter regional procedure is assessed by its sampling variance. Gumbel and GEV estimation uncertainty is quantified by the expressions collected in Lu and Stedinger (1992). Expressions for the TCEV were developed. Uncertainty of quantile estimation at ungauged sites is quantified by the residual variance of the regression equations.

5. Plans for future development

A multivariate analysis on peak-volume-duration variables is currently being carried out to develop a methodology to be applied in dam design, as a whole hydrograph must be known to design the spillway length of a dam. The first step is the frequency analysis of the hydrograph volumes to develop a regional method to estimate the volume frequency curve from observed data. Then, the relationship between the peak and the hydrograph volume is studied. The first results of this study can be seen in Mediero et al. (2010).

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7. Attachments

The application for the "Map of peak flows in the Tagus basin" can be downloaded from: http://www.marm.es/es/agua/temas/gestion-de-los-riesgos-de-inundacion/snczi/mapa-de-caudales-maximos/

The application for the "Map of peak flows" for the rest of basins can be downloaded from: http://www.marm.es/es/agua/temas/gestion-de-los-riesgos-de-inundacion/snczi/mapa-de-caudales-maximos/

UK – United Kingdom (Thomas R. Kjeldsen)

1. Description of method

The UK has a set of **procedures** for flood frequency estimation developed at the Centre for Ecology & Hydrology (previously the Institute of Hydrology). These procedures are outlined in a series of publications and have been adopted by most UK regulatory authorities as standard procedures to be used for flood frequency analysis and design flood estimation in the UK. The initial statistical procedures were published by NERC (1975) in the Flood Studies Report (FSR) and included an early version of the index flood method based on annual maximum series, a Generalised Extreme Value (GEV) distribution and a set of fixed geographical regions.

The FSR methods were applicable to all catchments in the UK, but for ungauged catchments relied on catchment descriptors derived manually from various paper maps. In 1995, a new project was initiated to update the FSR, which resulted in the publication of the Flood Estimation Handbook (FEH) by the Institute of Hydrology (1999). A major advance in moving from the FSR to the FEH was the introduction of digital catchment descriptors to replace the outdated paper maps. The digital catchment descriptors are derived based on an underlying 50 m dem covering all of the UK and are available for all catchments larger than 0.5 km^2.

Since the publication of the FEH in 1999, the statistical method has been updated again by Kjeldsen et al. (2008), which is a revitalised version of the index flood method published in the FEH. In the following, the technical aspects of the revitalised FEH flood statistics (ReFS) method are described.

1.1 Identification of homogeneous pooling-groups of sites

Pooling groups are formed using a site similarity measure based on catchment area (AREA), standard annual average rainfall (SAAR) as recorded in the reference period 1961-1990, an index of flood attenuation from upstream lakes and reservoirs (FARL) and an index of upstream extent of flood plains (ratio of 100-year flood plain compared to total catchment area). The similarity measure is defined as

$$d_{ij} = \sqrt{3.2\left(\frac{\ln[AREA_i] - \ln[AREA_j]}{1.28}\right)^2 + 0.5\left(\frac{\ln[SAAR_i] - \ln[SAAR_j]}{0.37}\right)^2 + 0.1\left(\frac{FARL_i - FARL_j}{0.05}\right)^2 + 0.2\left(\frac{FPEXT_i - FPEXT_j}{0.04}\right)^2}$$

Following methodological developments reported by Kjeldsen et al. (2008) and Kjeldsen and Jones (2009b), there is no longer a need for the pooling groups to be homogeneous. The difference of L-moment ratios (L-CV and L-SKEW) between catchments have been taken into account in the underlying statistical model.

1.2 Estimation of the index flood or site-specific scale factor

A log-linear regression model was developed linking the (log) index flood (median annual maximum flood) to a set of catchment descriptors.

$$QMED = 8.3062 AREA^{0.8510} 0.1536^{\left(\frac{1000}{SAAR}\right)} FARL^{3.4451} 0.0460^{BFIHOST^2}$$

This equation was based on annual maximum data from 602 non-urban catchments and has a fse=1.431. Details of the development of this model were presented by Kjeldsen and Jones (2009a).

A key-recommendation for the FEH/ReFS is the use of local data from nearby donor catchment. Consider the case where a flood estimate is required at an ungauged site, but gauged observations are available at a nearby site. In such cases the index flood (QMED) obtained using the log-regression model should be adjusted as

$$QMED_{s,adj} = QMED_{s,cds}\left(\frac{QMED_{g,obs}}{QMED_{g,cds}}\right)^{\alpha}$$

Where subscript *s* refers to the ungauged subject site and *g* is the gauged donor site. The subscript *cds* refers to the estimate of the index flood derived from catchment descriptors only, *obs* to the value at the gauged site and *adj* is the adjusted value at the subject site. The coefficient α is related to the general structure of the regression model errors and is given as

$$\alpha = 0.4598\exp\left(-0.020d_{sg}\right) + (1 - 0.4598)exp\left(-0.4785d_{sg}\right)$$

Where d_{sg} is the geographical distance (km) between the catchment centroids of the subject and donor sites. More details on the rationale behind donor transfer is provided by Kjeldsen and Jones (2010).

1.3 Choice of a frequency distribution

The ReFS retained the advice given by the FEH, i.e. to use the Generalised Logistic (GLO) distribution as default.

1.4 Estimation of the frequency distribution

Distribution parameters are estimated using the method of L-moments, but has adopted using the median, rather than the mean, annual maximum flood as the index flood variable.

2. Data

2.1 Catchment descriptors

The catchment descriptors underpinning the FEH/ReFS methods in the UK are derived from various datasets (and thus scales) and disaggregated down to catchment scale based on a 50 m national DTM and a dataset containing the UK river network digitized from 1:50000 maps. Numerous catchment descriptors are available representing: land-forms, lakes and reservoirs, climate, soils, and land-cover. The catchment descriptors are available for all UK catchments larger than 0.5 km^2 and a more detailed list of available descriptors can be found in Bayliss (1999).

2.2 Flood data

The primary source of instantaneous flood peak data in the UK are provided by the gauging authorities (Environment Agency, Scottish Environment Protection Agency and Rivers Agency) and made available for download through the HiFlows-UK data portal (http://www.environment-agency.gov.uk /hiflows/91727.aspx).

Both AMS and PDS are available for close to 950 gauging stations. Of these, about 100 would not be considered of sufficiently high quality to be used in flood studies, about 40 do not have associated catchment descriptors, and about 200 would be considered to be impacted by urban development. The average record-length of the remaining 600-odd sites is about 35-years. Records of daily flow (not normally used in flood frequency estimation) are available from the National River Flow Archive (http://www.ceh.ac.uk/data/nrfa/index.html).

3. Discussion

3.1 Purpose and areas of application

The FSR/FEH/ReFS were specifically designed to provide a set of techniques for flood prediction in the UK. Consequently these methods have become the recommended methods for use in the UK for flood frequency estimation for all but the most urbanized catchments, where urban drainage procedures are generally recommended. Note that the ReFS method as reported above was designed for application on non-urban catchments. For catchments containing a significant proportion of urban land-use, a set of adjustment procedures for the index flood and L-moment ratios were developed and published by Kjeldsen (2010).

3.2 Main features, merits and drawbacks

Most flood estimates in the UK are required for 100, 200 and 1000-year return periods. Under the normal caveats associated with extrapolation from no or short records, the ReFS method is generally used for estimating the design floods at these return periods at both gauged and ungauged sites.

5. Plans for future development

The methods are under constant development at CEH. Current projects include the development of catchment descriptors based on a national DTM with grid-size 5 m rather than the current 50 m. Other developments include optimal transfer from multiple donor sites and the inclusion of non-systematic historical evidence of flooding.

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TR – Turkey (ARTEMIS project, Dr. Gülay ONUŞLUEL GÜL, Dr. Ali GÜL)

1. Description of method

Many studies have been conducted using at-site flood frequency analysis (SFFA) in different parts of Turkey, whilst the application of regional flood frequency analysis (RFFA) is rather limited. The study performed by Seçkin et al. (2011) is the one that comes into prominence in the area of RFFA with wider geographical coverage in Turkey.

The ARTEMIS (Assessment of Flood Frequency Estimation Procedures under Environmental Changes) project in Turkey aims to carry out a study to characterize sub-basins defined at micro level in Turkish river basin systems, selecting a number of case studies based on this characterization and then applying SFFA approach through both classical and modern flood frequency estimation techniques. These analytical approaches will serve for assessing the feasibilities of different methods under existing methodological and data-related limitations in Turkey. The computations will be supported by hydrological simulations to assess impacts of land-driven and environmental changes that mainly include urban sprawl, climate change, etc.

In ARTEMIS project, a catchment characterization and clustering approach was performed for micro basins (extracted from the CCM2 database of the Joint Research Centre (JRC)(Vogt et al., 2007; Vogt et al., 2008) first for characterizing the sub-catchments and then making selection of pilot areas for SFFA analyses based on computed similarities/differences between the catchments. The grouping criteria were selected as given below:

- Share of open spaces and artificial surfaces in drainage areas
- Average terrain slopes computed for drainage areas
- Share of built-up land in micro basins receiving water from corresponding catchment areas of variable sizes
- Change in the relative share of built-up land inside catchments between the years 2000 and 2006.
- Mean annual precipitation and temperature measured for the 1961-1990 reference period within catchment areas draining into micro basins
- Estimated changes in mean annual precipitation and temperature between the reference period 1961-1990 and the scenario period 2010-2039
- Share of terrain sections above 1000 m in catchments and average rate of temperature increases in these areas (considering snow-melt triggered flood generation originating from higher altitudes.
- Availability of gauging stations inside catchments with sufficiently long records of observations
- Geographical boundaries of bio-geographic regions in Turkey

The above set of grouping criteria was then assessed together to make selection of pilot areas where SFFA will be performed in the following stages of the project.

1.1 Identification of homogeneous pooling-groups of sites

In the study by Seçkin et al. (2011), an RFFA by the index flood method was applied to the annual flood peaks series recorded at 543 unregulated gauging stations in Turkey (see Figure TR1) as the parameters of the selected distributions are estimated by the method of L-moments.

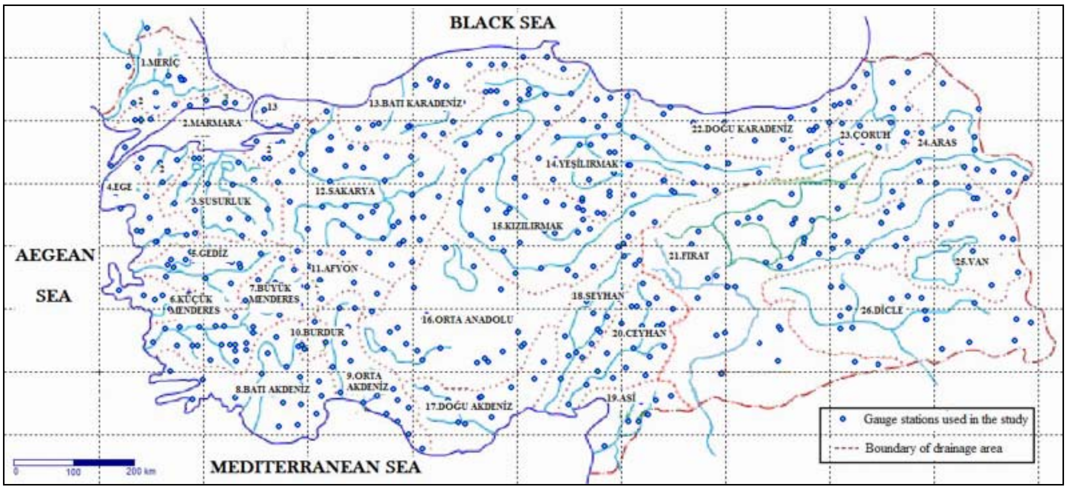


Figure TR1 Locations of gauging stations in Turkey (Seckin et al., 2011).

The numerical values of the site discordancy measure, Di, the heterogeneity measure, H and the goodness-of-fit measure, ZDIST, are computed for the whole region. As 45 of 543 gauged sites exhibit discordancy, they are discarded from the analyses.

Heterogeneity measures computed by carrying out 500 simulations using the data of 498 sites Resulted in values of both H(1) and H(2) greater than 2.0, which indicates that Turkey as a whole 'is definitely heterogeneous'.

1.3 Choice of a frequency distribution

Three pilot areas (from Eastern Black Sea, Seyhan and Euphrates River Basins) selected to this end are shown in Fig.TR-2. The pilot areas contain the sub-catchments which resulted from multi-criteria catchment characterization analyses as well as the areas draining into these identified sub-catchments, as shown in Figure TR-2.

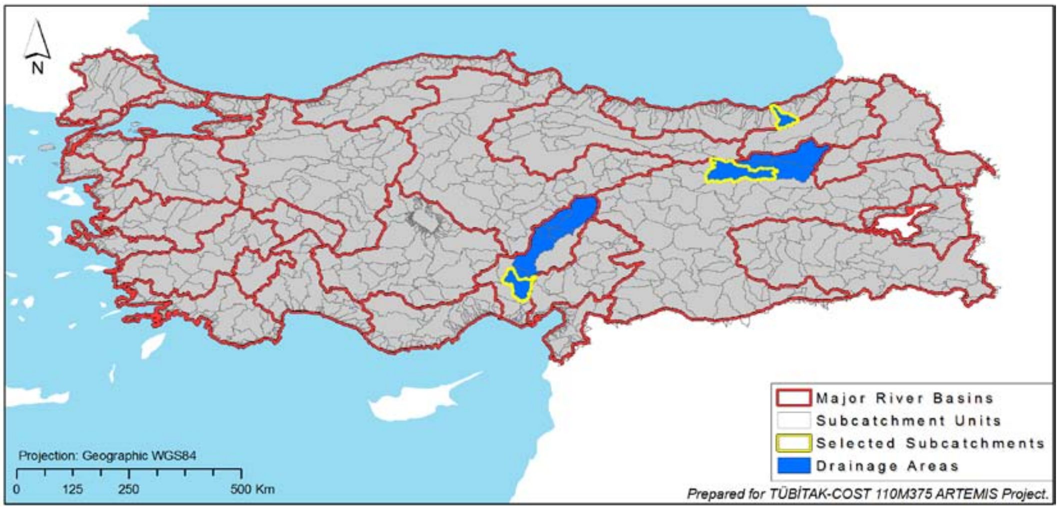
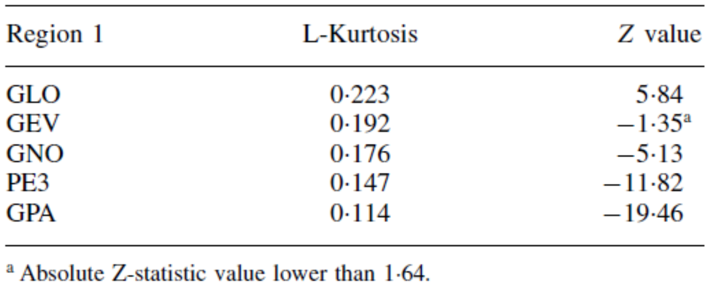


Figure TR2 Locations of pilot catchments identified for ARTEMIS Project, and pilot areas within Eastern BlackSea, Euphrates and Seyhan River Basins.

In each of the three pilot basins, a number of representative flow gauging stations were identified and the monthly maximum flow values measured in these stations in periods starting from 1930s and extending up to the year 2010 were tested for any existence of autocorrelations in time series data. Seven distributions including 2- and 3-parameter Lognormal, Gamma, Pearson Type 3, Log-Pearson Type 3, Gumbel and GEV distributions were applied in three pilot basins.

The goodness-of-fit values (ZDIST's) were computed for: generalized logistic (GLO), generalized extreme values (GEV), generalized normal, Pearson type III (PE3) and generalized Pareto distributions, as shown in Table TR2. Of these distributions the ZDIST is smaller than 1.64 only for the GEV distribution; and accordingly, the GEV distribution is the robust distribution for Turkey. Interestingly, Bayazit et al. (1997) also found the GEV distribution as having the best fit according to conventional statistical tests applied to the recorded annual flood peaks series in Turkey.

Table TR2 Values of the Z^{DIST} statistic of various distributions for Turkey.



Region 1	L-Kurtosis	Z value
GLO	0·223	5·84
GEV	0·192	−1·35[a]
GNO	0·176	−5·13
PE3	0·147	−11·82
GPA	0·114	−19·46

[a] Absolute Z-statistic value lower than 1·64.

1.4 Estimation of the frequency distribution

The regional flood frequency relationship for estimation of flood peaks of various return periods for Turkey is expressed as:

$$Q_T = \{-2{\cdot}281 + 2{\cdot}985(-\mathrm{Ln}\ F)^{-0{\cdot}136}\} \times \overline{Q}$$

The magnitude of the determination coefficient (R^2) of this equation is 0.91 (Seçkin et al., 2011).

Regarding at-site estimation of frequency distribution, the method-of-moments, maximum likelihood and L-moments were computed for 11 stations within the above catchment areas (5 stations for the pilot catchment in Seyhan Basin, 3 stations for the area in Euphrates Basin, and 3 stations for the pilot area in the Eastern BlackSea Basin). The distributions were then tested with the help of Kolmogorov-Smirnov, Chi-square and Anderson-Darling goodness-of-fit tests. Tables TR3, TR4 and TR5 present the conformity ranking for the distributions tested with measurements from corresponding flow monitoring stations.

Table TR3 Indications on goodness-of-fit tests applied for the catchment in Seyhan Basin

Goodness of fit (α=0.05)	1801				1805				1806+26				1818				1822			
		KS	AD	X^2		KS	AD	X^2		KS	AD	X^2		KS	AD	X^2		KS	AD	X^2
Lognormal 2	7	+	+	+	1	+	+	+	3	+	+	+	7	+	+	+	7	+	+	+
Lognormal 3	5	+	+	+	3	+	+	+	6	+	+	+	6	+	+	+	1	+	+	+
Gamma	2	+	+	+	7	+	+	+	7	+	+	+	1	+	+	+	5	+	+	+
Pearson 3	3	+	+	+	5	+	+	+	4	+	+	+	5	+	+	+	3	+	+	+
Log-Pearson 3	4	+	+	+	4	+	+	+	5	+	+	+	3	+	+	+	4	+	+	+
Gumbel	1	+	+	+	6	+	+	+	1	+	+	+	2	+	+	+	6	+	+	+
GEV	6	+	+	+	2	+	+	+	2	+	+	+	4	+	+	+	2	+	+	+

Table TR4 Indications on goodness-of-fit tests applied for the catchment in Euphrates Basin

Goodness of fit (α=0.05)	2119				2151				2154			
		KS	AD	X^2		KS	AD	X^2		KS	AD	X^2
Lognormal 2	7	+	+	+	6	+	+	+	4	+	+	+
Lognormal 3	6	+	+	+	4	+	+	+	5	+	+	+
Gamma	1	+	+	+	2	+	+	+	2	+	+	+
Pearson 3	2	+	+	+	7	+	+	+	7	+	+	+
Log-Pearson 3	4	+	+	+	3	+	+	+	3	+	+	+
Gumbel	5	+	+	+	5	+	+	+	6	+	+	+
GEV	3	+	+	+	1	+	+	+	1	+	+	+

Table TR5 Indications on goodness-of-fit tests applied for the catchment in Eastern BlackSea Basin

Goodness of fit (α=0.05)	2215				2218				2233			
		KS	AD	X^2		KS	AD	X^2		KS	AD	X^2
Lognormal 2	4	+	+	+	5	+	+	+	7	+	+	+
Lognormal 3	5	+	+	+	3	+	+	+	1	+	+	+
Gamma	2	+	+	+	7	+	+	-	6	+	+	-
Pearson 3	7	+	+	+	4	+	+	+	2	+	+	+
Log-Pearson 3	3	+	+	+	2	+	+	+	4	+	+	+
Gumbel	6	+	+	+	6	+	+	+	5	+	+	+
GEV	1	+	+	+	1	+	+	+	3	+	+	+

2 Data

2.1 Catchment descriptors

The catchment descriptors employed for the SFFA methods in the ARTEMIS project were derived from a number of national/international datasets and were used for determining pilot study sites as well as the pilot area-scale analyses. These mainly include average catchment slope, share of open spaces and artificial surfaces in catchments, share of highlands in catchments, estimated temperature increases in highlands, percentage of built-up land, change rate of built-up land (between the years 2000 and 2006), mean annual precipitation (MAP), mean annual temperature, estimated percent changes in precipitation and temperature between the reference period 1961-1990 and the scenario period 2010-2039, and biogeographic structure.

These descriptors were generated from various national/international datasets including digital elevation model (derived from a combination of ASTER-GDEM, national raster elevation datasets and vector elevation datasets from 1:25,000 and 1:50,000 scales and with 10m and 20m vertical resolutions, respectively), national hydrography dataset (collected from State Hydraulic Works), Turkey's climate zones dataset, regional climate model outputs (obtained from a national research project called "Climate Change Scenarios for Turkey" (http://gaia.itu.edu.tr/)), Corine Land Cover (CLC) vector and raster datasets from the years 2000 and 2006, and biogeographic regions dataset for Turkey.

2.2 Flood data

Instantaneous flood peak data in Turkey are provided by the gauging authorities (General Directorate of State Hydraulic Works (under Ministry of Environment & Forestry) and General Directorate of Electrical Power Resources Survey and Development Administration (under Ministry of Energy & Natural Resources)). AMS are available for 1364 gauging stations. Daily flow records are also available from the authorities mentioned above.

3. Discussion

Determining the most suitable probability distribution from data on annual flood peaks contributes to the planning, design and management of water resources projects.

Estimations on flood peaks of various return periods enable similar assessments at ungauged sites in Turkey, especially for designing hydraulic structures, assessing urban hydrology, mapping flood-hazard risks, etc.

4. Case studies

There are numerous examples of the practical applications of regional/at-site flood frequency analyses in Turkey. The most significant ones are presented in the following studies:

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5. Plans for future development

The next stage in statistical analysis will focus on testing and adaptation of modern frequency estimation techniques such as time-varying models, local likelihood approach, quantile regression method, etc.

In the final stage of the project, non-stationary flood frequency estimations will be made in pilot areas against estimated impacts of climate change on climatic variables.

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