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NIFS - Flood estimation in small catchments

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Abstract: This report is a literature review of flood estimation methods applicable to small catchments. The report summarizes characteristics of small catchments with respect to flood generation and estimation. It describes why flood estimation is particularly challenging in small catchments, and which aspects need specific consideration. Flood estimation methods for both gauged and ungauged sites are included, together with a summary of national methods and recommendations specific for small catchments from several countries.

Key words: Flood estimation, small basin characteristics, regionalisation, rainfall-runoff models.

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Preface

Natural hazards, such as floods and landslides are frequent in Norway and are causing damage to infrastructure in many parts of the country. The frequency of these hazards is expected to increase under climate change, particularly in small catchments. In order to reduce the risk connected to natural hazards, the national NIFS project (Natural hazards – Infrastructure -floods - landslides) has been established and is a cooperation between three Norwegian agencies for the railway (Jernbaneverket), public roads (Statens vegvesen) and water resources (Norwegian Directorate for Water Resources and Energy). An important requirement for more robust infrastructure is the ability to consider natural hazards at the planning stage for new infrastructure or the maintenance of existing infrastructure. Flood estimation in small catchments is a particular challenge since data is often either not available or is only available at a daily time step. One of the objectives of NIFS is therefore to develop guidelines for flood estimation in small catchments. This report reviews existing methods for flood estimation in small gauged and ungauged catchments.

Oslo, October 2013

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Summary

This report is a literature review of flood estimation methods applicable to small catchments. The report summarizes characteristics of small catchments with respect to flood generation and estimation. It describes why flood estimation is particularly challenging in small catchments and which aspects need specific consideration. Methods for flood estimation in both gauged and ungauged sites are included, together with a summary of national methods and recommendations specific for small catchments.

In practise, empirical (regional) methods for flood estimation in small catchments dominate. However, these methods are often unsuitable for application in other regions or to catchments with differing characteristics. An important issue for flood estimation in small ungauged catchments is the adequate representation of catchment characteristics. For this, information with a high spatial resolution is needed. However, the resolution of most GIS databases is insufficient, and several countries such as Austria, Germany and Switzerland therefore stress the importance of site visits and catchment mapping. The methods currently used and or under development in Austria, Switzerland and the UK offer promising approaches, which could be adapted and tested for application in Norway. In addition, Bayesian approaches and the further development of rainfall-runoff models particularly for small catchments may prove useful.

1 Introduction

In Norway, estimates of flood magnitudes and probability are needed for dam design and safety assessments, flood risk management and spatial planning. Two kinds of approaches are generally used to estimate design floods: 1) *Statistical flood frequency analyses* based on observed data, and 2) *rainfall-runoff models*, as reviewed by Wilson *et al*. (2011). Flood frequency analysis uses observed flood time series and to estimate the discharge of flood events with a certain return period. Various methods exist for flood frequency analysis, both when observed series are available for the study site (at-site frequency analysis) and when using flood data from other stations (*regional frequency analysis*). The latest approaches, currently largely only used in research studies are *climate/weather-informed at-site frequency analysis* and *historical and paleoflood analyses* (Renard *et al*., 2013). Rainfall-runoff modelling on the other hand makes use of observed precipitation data as input into a hydrological model to estimate the flood discharge. The hydrological model can either be calibrated when discharge data for the study site are available, or model parameters can be estimated from catchment characteristics. In addition to flood magnitudes corresponding to a certain return period, rainfall-runoff models can be used to estimate the probable maximum flood (PMF). In Norway, PMF is often needed for dam safety assessments. Both approaches have their advantages and disadvantages, and it is commonly recommended to compare the results obtained with different methods. Of the large number of available *empirical methods* this report includes only the most common ones that are frequently used for small catchments and the design of stormwater drainage structures. *Empirical methods* are usually developed for flood estimation in cases where observed hydrological data are not available, and are typically based on the estimation of one or more catchment parameters. Most of the formulas give an estimate of maximum peak flow (in a region) without giving its probability. Fewer allow estimation of the peak flow for a defined return period. The “Norwegian Water Management Handbook” (Vassdragshåndboka, Fergus *et al*., 2010) and an NVE report on practical urban hydrology (Bøyum *et al*., 1997) also recommend the use of the rational method in some instances (typically for the dimensioning of culverts and pipes in the absence of flood data), which is an empirical method applied internationally.

Flood estimation is usually straight forward when sufficiently long observations of good quality are available for the site of interest, as outlined by Wilson *et al*. (2011). It can, however, be a challenge when needed for an ungauged catchment. This is particularly the case for small catchments, since the statistical approach recommended for use in Norway is inappropriate for such sites due to a lack of both at-site data and the availability of representative data from nearby gauges. In addition, rainfall-runoff modelling in small catchments is hampered by a lack of both observed discharge and precipitation data. Hence, the problem is that available flood estimation methods have often been developed using observed hydrological records which seldom include data from small catchments, since larger catchments have traditionally been the focus for hydrological monitoring and data collection. Consequently, a large number of different empirical methods have been devised and are still used by practitioners for flood estimation in small catchments. However, for many of these methods it can be difficult to find out for which conditions they are applicable and to judge the quality of the result.

With respect to infrastructure, damages caused by floods in small catchments is one of the most challenging issues. As part of the national NIFS project (Natural hazards – Infrastructure - floods - landslides) guidelines for flood estimation in small catchments in Norway are therefore being developed. As a first step, this report provides a literature review of existing and commonly used approaches for flood estimation in small catchments considering both research studies and national guidelines for practitioners. Flood estimation in small catchments is particularly difficult in the case of ungauged catchments or sites with only short data records. Many small catchments are ungauged, and the main focus of this report is therefore on methods for flood estimation in *small ungauged catchments*.

Small urban catchments are a special case, due to the relatively high proportion of the total catchment area that is inundated and the presence of artificial flow structures (pipes, culverts, etc). In many countries, improved flood risk estimation in urban catchments in changing environments is currently a key research topic with respect to flood estimation in small catchments. In Norway, however, flood estimation in small non-urbanized catchments in rural, forested or mountainous areas is also of major importance, where infrastructure such as roads and railways can be frequently damaged by local flood events. This literature study focuses solely on flood estimation in non-urbanized areas.

The availability of good methods for flood estimation in small catchments is also an important task with respect to Norway’s strategy for adaption to climate change. Heavy, local precipitation events are expected to increase in the future, which could increase the occurrence of severe floods in small catchments (Lawrence & Hisdal, 2011).

This report reviews existing methods for flood estimation in small catchments, both for practical application and research. The report starts by defining small catchments, and outlining and why they should to be treated differently from larger ones (Section 2). Then, a general overview over existing approaches for gauged (Section 3) and ungauged (Section 4) catchments is given, before summarising national methods and recommendations specific for small catchments from different countries (Section 5). The need and possibilities for considering non-stationarity, and the influence of climate change are discussed in Section 6. Finally, the results are summarized and conclusions drawn.

2 Small catchments

2.1 Flood producing processes and catchment characteristics

The peak discharge response of a catchment to rainfall is a function of a number of variables, including rainfall rate, space-time variability, and catchment characteristics such as soil moisture and infiltration capacity, groundwater storage, land use/land cover, and geomorphology. The relative importance of these factors depends on the runoff producing mechanism and size of the catchment (Ogden & Dawdy, 2003). This makes flood estimation methods developed on larger catchments often unsuited for smaller ones. Extreme peak flows in larger catchments are mostly caused by long lasting precipitation events of lower intensity and/or snow melt. In smaller catchments, on the other hand, the most extreme peak flows can be caused by local convective precipitation events with high intensity (Lorenz *et al*., 2011).

Flood estimation in small catchments is particularly difficult since:

(1) flood peaks in small catchments are more susceptible to the influence of local features, such as flow diversions, field drainage, or the storage of flood water behind culverts, bridges and embankments (Environment Agency, 2012), and (2) local extreme precipitation events can result in higher peak flows relative to the average flow then in larger catchments, so that comparison with larger neighbouring catchments might be little informative (Lorenz *et al*., 2011). (3) appropriately describing the local hydrological processes crucial for reliable flood estimation in small catchments is not easy, since flood generation can be dominated by few processes compared to larger catchments where an averaging of processes over a larger spatial area takes place (Spreafico *et al*., 2003). (4) typically, flow data are not available, or (5) can more frequently be subject to undetected measuring errors (Lorenz *et al*., 2011). (6) observed data need to follow particularly high quality standards, as for instance, local land use changes might have significant effects on the hydrological processes in a small catchment, possibly causing large non-stationarities in the flood time series. (7) observed data should furthermore be available in high temporal resolution, due to the fast response and flow fluctuations in small catchments (Bøyum *et al*., 1997). In particular, mean daily observations can differ considerably from observed instantaneous flood peaks in small fast responding catchments (Wilson *et al*., in press). Further differences and non-stationarities occur when automatically recorded observation series are extended by data obtained from manual readings once a day. (8) observed precipitation data from a representative station are rare and would be needed in a high temporal resolution (Bøyum *et al*., 1997). (9) generally few data records from small catchments are available, which could be used to calibrate estimation methods for ungauged catchments (Spreafico *et al*., 2003). In Norway, the data availability is now slowly improving and the available data for catchments smaller than 50 km^2 have recently been summarised (Stenius, 2012).

2.2 Definition of small catchments

The different flood estimation guidelines may define small catchments differently. This depends, in part, on the typical hydrological and topographical characteristics of a country or region. In many scientific studies a clear definition, of what is considered a small catchment is lacking. In the UK, small catchments are generally described as being less than 20 – 25 km^2 (e.g. NERC, 1975; IH, 1999). In New Zealand catchments below 30 km^2 are considered small. However, in the development of flood estimation methods used in New Zealand catchments up to 100 km^2 were used. In Austria flood estimation for small alpine catchments (torrents) is most frequently performed for catchments of 5 – 10 km^2, but some are also larger than 20 km^2, or smaller than 1 km^2 (Hagen *et al*., 2007). The current Austrian flood estimation guidelines (Lorenz *et al*., 2011) recommend differentiating between medium sized (10 – 500 km^2) and small catchments (< 10 km^2). The same distinction is made by the Swiss authorities (Spreafico *et al*., 2003). In a Slovakian study on regionalization for ungauged basins, catchments up to 200 km^2 are defined as small (Kohnová *et al*., 2006). Also in a Polish case study for flood estimation in gauged and partially gauged small catchments, the example basins are 82 km^2 and 187 km^2, respectively (Banasik & Byczkowski, 2011).

According to the "Norwegian Water Management Handbook" (Vassdragshåndboka, Fergus *et al*., 2010) very small (< 0.5 km^2), small (< 20 km^2) and large catchments are often distinguished prior to flood estimation in Norway. In the Norwegian Guidelines for Flood Estimation (Midttømme *et al*., 2011), catchment size is not classified. Instead, the guidelines specify the suitability of each recommended method according to catchment size. In the context of comparing new results to the experience from previous studies (in the same region), Midttømme *et al*. distinguish between small (< 50 km^2) and medium sized catchments (50 – 500 km^2).

In general, different definitions of small catchments currently exist in Norway, usually dependent on the required application. In an evaluation of the discharge station network in Norway, catchments below 150 km^2 are referred to as small (Leine *et al.*, 2013), whereas a recent work (Stenius, 2012) detailing all small gauging stations with available data in the national hydrological database considers catchments up to 50 km^2. To protect infrastructure such as roads and railways from floods and landslides, information about catchments of a few square kilometres can be relevant.

In a case study in the south-eastern part of Norway, Skaugen (*pers. comm.*) found precipitation series at about 5 km distance to be uncorrelated. This can make it necessary to treat catchments of a few square kilometres differently, as they are more likely to be uniformly covered by extreme (convective) precipitation events. The current regional formulas for flood estimation in ungauged catchments in Norway are in regarded as valid for catchments with areas < 100 km^2 (Midttømme *et al*., 2011). At NVE more than half of the flood estimations performed in recent years (2007-2011) were requested for catchments below 20 km^2, and about 25% for catchments below 5 km^2 (Væringstad, *pers. comm.*). This stresses the need for valid, reliable flood estimation methods for the whole range of catchment sizes, below 100 km^2.

Following international experience, it might be useful to test whether different approaches should be developed and used in Norway for catchments below and above 10 km^2 as in Austria and Switzerland, or whether a separation should be made around 20 – 25 km^2 as in the UK. In any case, classification should be based on the validity of the recommended methods. One starting point could be to analyse the spatial dependence of the flood generating processes in Norway. For instance, the critical catchment size should be identified below which the entire catchment frequently experiences the same precipitation event or where floods produced by local convective storms dominate. Furthermore, the size above which a catchment includes enough spatial variability in catchment characteristics to be well enough represented by the regional average should be considered. However, this is likely to be a difficult question to answer, but it could be easier than identifying the relative importance of specific processes across scales, which is still an important research question (e.g. Blöschl *et al*., 2007).

3 Flood estimation in gauged catchments

In case of gauged catchments with long data records of good quality, flood estimation methods do not need to differ from those applied to larger catchments. Challenges might however arise due to required data quality, due to the potential differences between manual stage readings performed once a day, daily means and instantaneous peak flows (see Section 2.1). Recommendations on which method to use depend on the purpose of the study and the availability and length of observed discharge series. When at least 30 years of good quality data are available for the catchment, *statistical flood frequency analysis* is usually considered the best option for flood estimation of different return periods. *Rainfall-runoff models* (see Section 4.3) can be used when the probable maximum flood (PMF) is needed. In Norway this may be required for dam safety assessments. In case of shorter observed series, flood frequency analysis can also be performed, but the uncertainty of the estimates needs to be evaluated with respect to the used data. Additionally, based on different methods should be compared. For this the same methods as for ungauged catchments can be applied, with the difference that the estimation of catchment parameters can be backed by the observations. When (short) series of both high resolution flow and precipitation data are available, the unit hydrograph approach can be used (see Section 4.3)

3.1 Statistical flood frequency analysis

For gauged catchments with at least 30 years of good quality data, statistical flood frequency analysis is straight forward independent of catchment size, as e.g. described for Norway by Wilson *et al*. (2011). However, as described in Section 2.1 special considerations apply for small catchments due to the quality of the observed data. Furthermore, the length of the series needs to be evaluated against its representativeness. Changes in the river regime, the profile or human intervention in the catchment, might have changed the flow and flood characteristics.

3.2 Rainfall-runoff modelling

The use of rainfall-runoff models is an alternative approach for estimating floods at a range of return periods in both gauged and ungauged catchments, and is used when the probable maximum flood (PMF) is needed or in case of longer series of observed precipitation than river flow. Rainfall-runoff models can be calibrated using precipitation and hydrological observations. Particularly important for small catchments is the need to adjust the time step of the model, which is dependent on the time of concentration of the catchment. Descriptions and instructions on the rainfall-runoff models commonly used in Norway can be found in Wilson *et al*. (2011), Midttømme *et al*. (2011) and Bøyum *et al*. (1997).

4 Flood estimation in ungauged catchments

4.1 At-site methods

A large number of different empirical methods have been developed for flood estimation in small catchments. This is probably due to both the large differences in the catchment characteristics of small catchments, combined with the general lack of observations. Methods have been derived based on observations from single flood events or continuous flood series. Purely empirical methods range from being based solely on catchment area, to having several parameters which describe catchment characteristics in various ways. Some of the methods consider precipitation as input, others do not. However, most of the methods have been developed for flood estimation in a certain region or for catchments with specific characteristics. No methods can be considered universal. Since empirical parameter values are derived from a limited number of catchments, and it is often recommended to verify the suitability of the applied method by comparison with other flood estimates in the region, only the most common methods are described here.

The Rational Method

In the traditional form of the rational method, the peak discharge, *q*, is estimated as a linear function of the runoff coefficient, *C*, rainfall intensity, *i*, and catchment area, *A*, in the form (e.g. Pilgrim & Cordery, 1993):

$$q = CiA$$

For application in flood estimation, the rainfall intensity and runoff coefficient are chosen for an event of a certain return period. The rainfall intensity is taken to be the average over the critical storm duration, which is assumed to be equal to the time of concentration of the catchment. The time of concentration is the time it takes from the start of a rainfall event until the whole catchment is contributing to the river flow at the gauging station. Hence, the two catchment coefficients, i.e. the runoff coefficient and the time of concentration have to be estimated for application in ungauged catchments. Both are usually estimated from empirical formulas or tabulated values, and several authors have suggested varying formulas. For successful application of the method, the estimate of the runoff coefficient is particularly crucial, as it has to account for all factors affecting the relation of peak flow to average rainfall intensity other than area and response time. Originally the method was developed for small rural catchments, but it is not specified for which catchment sizes the method is valid. However, a basic assumption is that the whole catchment is more or less uniformly covered by a rainfall event of constant intensity, which limits its application for larger catchments. Many different modifications of the rational formula have been developed and are in use. Adjustments have been made to better represent certain conditions, for instance in very small or somewhat larger catchments of a few 10s of km^2, natural catchments or a certain region (e.g. Sections 5.2.2, 5.2.3, 5.3.7).

Soil Conservation Service Method (SCS)

The Soil Conservation Service Method (SCS-method) relates runoff depth and rainfall during a flood event by the runoff curve number, *CN* (e.g. Pilgrim & Cordery, 1993). Peak flow is then estimated using runoff depth, lag, time of concentration and rainfall duration. For the estimation of a flood event of a certain return period, the rainfall event of the same return period is chosen. Tabulated empirical values for the runoff curve number, *CN*, are available for different antecedent moisture conditions, soil type and land cover (which also considers the differing hydrological surface properties of vegetation in good and poor condition). Antecedent moisture conditions are specified by three classes (dry, average, wet) and soil type by four (high, moderate, slow, very slow infiltration). Time of concentration can be estimated by various general procedures, which are not developed particularly for the SCS-method. Some evaluation studies suggest however, that the method does not perform equally well under all conditions. It seems, for instance, to be more suitable for bare soil and sparse vegetation than dense vegetation. The estimate of the time of concentration can be more relevant than the influence of *CN* and catchment characteristics. Furthermore, the effect of the assumed antecedent moisture conditions on the results can be large (Hoesein *et al*., 1989). Care is therefore required in its application and Pilgrim & Cordery (1993) recommend comparing the results to observed flood data in the region. In more recent applications it is further recommended to replace the empirical standard value for the initial abstraction ratio, λ, by a local estimate (e.g. Grimaldi et al., 2012; λ relates the initial abstraction, i.e. the minimum rainfall amount for runoff to occur, to the potential retention, i.e. the maximum possible difference between the rainfall amount and runoff for increasing rainfall amounts).

4.2 Regionalisation methods

Regionalisation methods are used to assist flood estimation at the site of interest, using information on flood characteristics of other comparable sites in the region. This is used when no or insufficient at-site data are available. Regionalisation methods are also applied to gauged catchments, when use of additional data is expected to reduce the uncertainty in the local flood estimates. Besides the large number of empirical formulas, which have been developed for a particular region, no regionalisation methods specific to flood estimation in small catchments have been found as part of this review. These empirical regional formulas are not presented here, as they are usually not applicable to catchments outside the target region. Some of them can be found in the country reports in Section 5. The applicability of general regionalisation methods for flood estimation in small catchments depends largely on the representativeness of meteorological and catchment characteristics at the sites used to derive the regional formulas as well as the available data (in particular size of gauged catchments and density of the station network). Common regionalisation methods worth considering for flood estimation in small catchments are described briefly below.

Envelope curves

Envelope curves for "flood discharge over catchment area" are defined for observed flood events in a region (e.g. Hagen *et al*., 2007). The method is most frequently applied when only an observation from a single/few flood events are available from several stations rather than complete flood series. Peak flow of all observed flood events in a region are plotted over catchment area, and an envelope curve is drawn as upper boundary, representing a maximum observed flood. Figure 1 shows an example from Switzerland, together with several empirical methods, which had been developed as envelope curves. Regression analysis is used to derive flood estimates for ungauged sites from the envelope curve, often using catchment area as the only regression parameter or a limited number of coefficients. The flood estimates hence correspond to a “maximum flood to be expected”. Return periods cannot be derived. If a flood estimate for a particular return period is needed, longer flood series from similar catchments in the region are required. For these catchments, flood frequency analysis is performed and the estimated flood magnitudes for the desired return period are plotted against catchment area to derive an envelope curve for a specific return period. This is similar to the quantile regression approach (see below) with the difference that the envelope curve is plotted as an upper boundary rather than an average best fit.

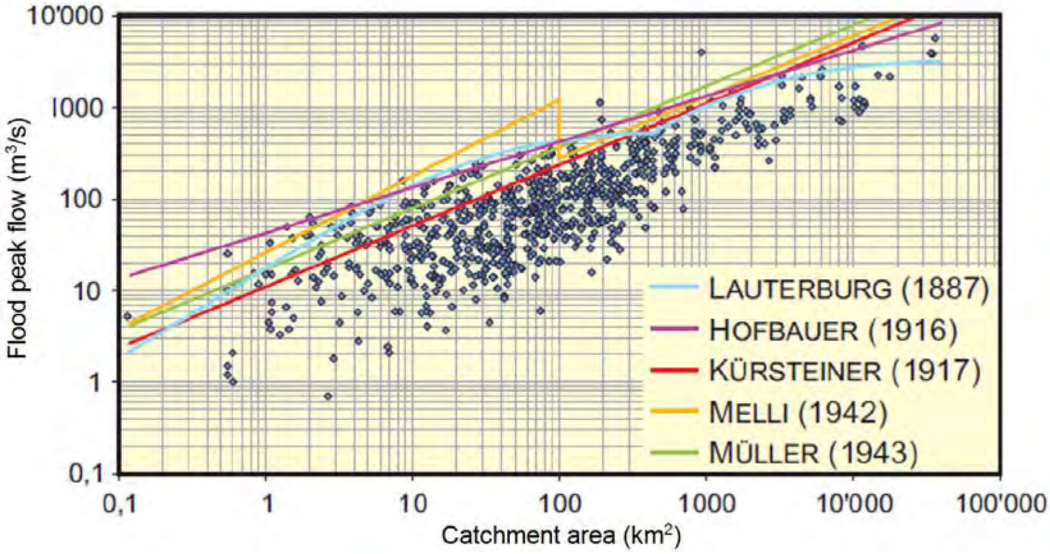

Figure 1 Several empirical envelope curves for the maximum flood to be expected together with flood peak flow observations in Switzerland (after Spreafico & Weingartner, 2005).

Index flood and regional growth curve approach

The most commonly applied regional approach is the index flood and regional growth curve method. It is based on the assumption that the flood frequency distributions of all stations in a predefined homogenous region follow the same normalized regional probability function, the so called growth curve (e.g. Wilson *et al.*, 2011). The flood frequency curve for the station of interest is then calculated by multiplying the growth curve by a scaling factor, the index flood. The mean or median flood derived from the annual maximum series of discharges is typically applied as index flood. The index flood can be derived from at-site observations (in Norway at least 10 years), correlation with neighbouring catchments or empirical regional formulas. However, the regional formulas used to derive the index flood in Norway (Sælthun, 1997) have been found to be less suitable for small catchments. This is likely caused by a low station density relative the heterogeneous flood conditions. In particular, few small catchments were included when the regional regression equations were established.

When using the index flood and regional growth curve approach, the identification of homogeneous regions is the first step, for which a large number of approaches are available and are currently in use. Wilson *et al*. (2011) summarize the following approaches: (1) the delineation of fixed, geographically coherent regions according to administrative borders or general knowledge of geographical, hydrological and climatic conditions, (2) the identification of homogenous groups of sites based on different kinds of hydrological or catchment characteristics using various statistical methods (e.g. cluster analysis, empirical orthogonal functions, split-sample regionalisation), and (3) the identification of a suitable group of stations similar to the individual site of interest. The latter is called the *Region of Influence approach* (ROI) and the groups of stations specific to a site are called pooling groups. Pooling groups are identified based on a similarity measure of the catchments. For example the similarity measure used in the UK is based on catchment area, standard annual average rainfall, an index of flood attenuation from upstream lakes and reservoirs and an index of upstream extent of flood plains (ratio of 100-year flood plain compared to total catchment area; Kjeldsen, 2012). Weights are assigned to all catchments in a pooling group according to the similarity measure, when deriving the growth curve. This accounts for the fact, that the catchments are indeed not similar. In summary, the following aspects need to be considered in the application of the ROI: (i) formation of pooling groups; (ii) weights applied to individual stations within pooling groups; (iii) size of pooling group; and (iv) performance of method (Kjeldsen & Jones, 2009).

Top-kriging

Top-kriging, or topological kriging is a geostatistical regionalisation approach which takes both, catchment area and the nested nature of catchments into account (Skøien *et al*., 2006). The flood discharge for a certain return period can be estimated for ungauged sites based on top-kriging analysis of the flood discharges of the same return period from gauged sites. The method requires a rather dense station network and flood measurements of nested catchments. These requirements can currently not be met in Norway.

Bayesian Model

In research applications, Bayesian models (e.g. Ribatet *et al*., 2007) and Bayesian hierarchical models (e.g. Lima & Lall, 2010) have been used for regional flood estimation, and a few countries such as France (Lang, 2012) include Bayesian models in their recommendations for flood estimation. Bayesian models make use of prior information and can for instance also be applicable to peak-over-threshold peak flow data (e.g. Ribatet *et al*., 2007). A further advantage is that they can be less restrictive to the definition of homogeneous regions as compared to the traditional index flood approach. Renard (2011) further suggested a Bayesian hierarchical model for regional frequency analysis which does not require the assumption of scale invariance. The latter needs, however, some further development for the application to hydrological variables rather than precipitation.

The Bayesian model suggested by Viglione *et al*. (2013) is part of the Flood Frequency Hydrology approach developed in Austria (see Section 5.3.1), which allows inclusion of several different kinds of information into the flood estimate, such as temporal information on historic floods, spatial information from neighbouring catchments and causal information on the flood processes.

Quantile regression method

In the quantile regression method, each flood quantile is separately regressed using catchment characteristics as independent variables. Here, the scaling factor of flood characteristics for catchments with different areas depends of the chosen probability of exceedance (return period). Flood quantiles, *Qp*, in a catchment with area *A* are estimated as:

$$Q_p(A) = C(p)A^{\theta(p)}$$

where both the coefficient $C(p)$ and the exponent θ (p) are functions of the probability of exceedance p. The exponent θ often decreases as p increases (Ogden & Dawdy, 2003). Besides catchment area, other catchment characteristics can also be included as regression parameters. Using several catchments characteristics, the quantile regression approach can therefore deal better with regions in which physiographic characteristics vary significantly as compared to the simple index flood approach (Fill & Stedinger, 1998).

4.3 Rainfall-runoff modelling

Rainfall-runoff models are used to estimate peak discharge using rainfall data as input. Their use can be favourable when longer precipitation records are available than runoff, or when precipitation can be more reliably estimated from surrounding stations (Wilson *et al.*, 2011). Rainfall-runoff models furthermore allow the estimation of the probable maximum flood as opposed to only flood magnitudes for different return periods. Most models need, however, to be locally calibrated based on precipitation, temperature and runoff observations. Only models where the parameters can be estimated by other means can therefore be applied to ungauged sites.

Another challenge when applying rainfall-runoff models to small catchments is that often observed precipitation data are not available. The quality of the flood estimates derived using hydrological models therefore largely depends on the quality of the estimated precipitation input and its representativeness of areal precipitation in the catchment under study. Since the spatial variability in precipitation is particularly large for extreme precipitation events (e.g. due to local convective precipitation), the uncertainty in the estimated precipitation data for a particular catchment can also be large. The uncertainty in the precipitation input can also be high, as precipitation events of certain return periods also need to be estimated based on a frequency analysis. Papalexiou *et al.* (2013) recently found that the most commonly used Gamma distribution underestimates daily precipitation extremes, compared to the best fitting Pareto or Lognormal distributions. Based on an analysis of more than 15,000 daily rainfall records from around the world with between 50 to 172 years of data, they found that the more heavy-tailed distributions (such as the Pareto or Lognormal) better represent the extreme events.

Besides the general distinction between lumped and distributed hydrological models, further differentiation can be made between event-based and continuous rainfall-runoff models. Event-based models typically apply intensity-duration-frequency curves for the estimation of extreme precipitation events, one of the simplest examples being the unit hydrograph (see below). Drawbacks of this approach are, however, that similar return periods for design rainfall and discharge are frequently assumed, possible inaccuracies due to the simplicity of the critical rainfall duration concept and difficulties in specifying pre-event soil-moisture conditions (e.g. Grimaldi *et al.*, 2012). But a precipitation event of a certain return period does not necessarily lead to a flood event of the same return period since precipitation can come either as snow or rain, due to variation in the saturation of a catchment prior to the event-precipitation, and because snow melt can occur in addition to rain.

When using rainfall-runoff models for flood estimation in small catchments, it has to be assured that the model used is adequate for representing the fast response times. A high temporal resolution is therefore needed (in Norway typically 1- to 3-hourly for catchments smaller than 100 km^2; Midttømme *et al.*, 2011), and the diurnal temperature variation, as well as diurnal variability in snow-melt might be needed.

Some models frequently used or recommended for flood estimation in small catchments are summarized below.

Unit Hydrograph

The unit hydrograph approach is based on the assumption that the shape of the hydrograph resulting from a rainfall event of a specified duration and large enough to exceed the infiltration capacity of the catchment will always be the same (e.g. Pilgrim & Cordery, 1993). As such the flood hydrographs resulting from rainfall events of varying intensities can be derived by scaling of the unit hydrograph. However, the unit hydrograph has to be defined for each catchment separately, where possible from rainfall and runoff observations. Alternatively, empirical formulas can be used to derive the unit hydrograph from physiographic catchment data for ungauged catchments. However, the use of the formulas is only recommended for catchments in the regions for which they were developed. No estimation methods for the unit hydrograph of natural catchments in Norway are known and standard unit hydrographs of natural catchments are used in practice. For small catchments with observed rainfall and flood events, on the other hand, the unit hydrograph approach is a very useful method (Bøyum *et al.*, 1997) and can be applied even when only a few flood observations are available. However, both hydrograph observations and recording rain gauge data are needed. A detailed description of the method can be found for instance in Pilgrim & Cordery (1993).

PQRUT

PQRUT is a simple, lumped, event-based precipitation-runoff model. It is a simplified version of the well-known HBV model and currently used for flood estimation in small catchments in Norway (see also section 5.1; Wilson *et al.*, 2011). The HBV model used operationally in Norway is not appropriate for flood estimation in small catchments, as it is only implemented on a daily time step. PQRUT can be used to calculate the PMF as well as flood discharges of a certain return period using a rainfall event of the same return period as input. The model is described in more detail e.g. in Wilson *et al*. (2011) and Midttømme *et al*. (2011).

Ongoing research

Several authors have recently suggested rainfall-runoff modelling approaches for small basins (e.g. Banasik, 2011; Grimaldi *et al*., 2012). Banasik (2011) tested the SEGMO Model (Sediment Graph Model) for estimating flood flows due to heavy rainfall in a catchment of 82 km^2 in Poland. For this study, only the hydrologic sub-model of SEGMO was used (i.e. without the sedimentology sub-model). This rainfall-runoff model estimates effective rainfall and the instantaneous unit hydrograph (IUH) based on the Soil Conservation Service CN-method. For the considered catchment, 20 years of observed data were available. Flood estimates obtained by the rainfall-runoff model as response to the 20-, 100- and 200-year rainfall events were compared to estimates of a seasonal flood frequency analysis using the observed discharge data. With a relative difference of 9-13% for the 100- and 200-year events between the two approaches, the author concluded that the rainfall-runoff method seems it be useful for flood events with a 100-year return period and higher but not for the 20-year flood (relative difference 71%). However, a lot of further work is needed especially with respect to parameter estimation for ungauged catchments.

Grimaldi *et al*. (2012) took it a step further by suggesting a continuous simulation model consisting of four steps: 1. simulation of daily rainfall and disaggregation into 15 min rainfall, 2. analysis of rainfall excess using the Soil Conservation Service-Curve Number model (SCS-CN), 3. derivation of a synthetic runoff scenario based on a geomorphological rainfall-runoff model, the width-function instantaneous unit hydrograph (WFIUH), and 4. estimation of the synthetic design hydrograph (SDH) following a multivariate flood frequency approach which considers both peak flow and volume. For the application to ungauged catchments, they assumed the availability of a longer daily rainfall record and shorter series of fine-scale rainfall observations, a standard digital elevation model (20-30 m resolution) and soil-use maps (e.g. CORINE 2000) or similar information. The model then has four parameters which need to be "guesstimated": the initial abstraction ratio (λ) and the curve number (CN) both related to the SCS-CN infiltration scheme, T_s, used to separate rainfall events, and T_c, the concentration time. Based on the application of the model to the Wattenbach catchment (72 km^2) in the Austrian Alps, they found that the effect of T_s is negligible compared to the other parameters, so that it can be set *a priori*. Also for λ a standard value can be used, when local values are not available. Even with the remaining two parameters, the model provides useful results, but in ongoing research the authors aim to further improve the infiltration scheme. In general, they suggest the model may be useful for small basins with a drainage area of less than 150 – 200 km^2, for which linear behaviour can be assumed and an instantaneous unit hydrograph applied.

5 Country reports

5.1 Norway

The methods currently recommended for flood estimation in Norway irrespective of catchment size, have recently been summarized and described by Wilson *et al*. (2011). When flood estimates for high return periods or the PMF are need (e.g. for dam safety assessments), the Norwegian rainfall-runoff model PQRUT is recommended for small ungauged catchments (1 – 200 km^2) and in particular for catchments where snowmelt related floods are of minor importance compared to floods caused by heavy rainfall events. Regional flood frequency analysis is only recommended for catchments larger than 20 km^2. A separate regional flood frequency analysis for small catchments is being developed within the NIFS project. For very small catchments in urban areas the rational method is further suggested. Whenever possible, results derived with different methods or for comparable catchments in the region should be compared. For this, typical values based on previous experience are given for the different regions in Midttømme *et al*. (2011). The values specified for small catchments are based on experience from catchments smaller than 50 km^2.

Bøyum *et al*. (1997) suggest the use of the rational method to get a rough flood estimate in small catchments with a homogeneous surface. They also specify typical values for the runoff coefficient for different catchments surfaces. However, they do not specify, how the values for the runoff coefficient were derived, i.e. whether they are standard values given with the first development of the method or whether they have been derived from experience with Norwegian catchments.

For flood estimation in small catchments, the PQRUT model is frequently used for dam safety assessments. For peak flow estimation in small catchments, the model needs to be run with a one- to six-hour time step. Usually, the high resolution precipitation and runoff data required for model calibration are not available. The three parameters of the PQRUT model need therefore, to be estimated using empirical equations based on catchment characteristics. These empirical equations were developed in 1983 (Andersen *et al*., 1983) based on data from 20 catchments. A re-evaluation of these equations, using the longer time series of high resolution runoff and precipitation data now available is recommended (Wilson *et al*., 2011).

Ongoing work

The Norwegian meteorological institute is currently updating intensity-duration-frequency curves (IDF) for extreme short term precipitation. As part of the work, IDF values for the whole country will be estimated and presented as map and research on short term precipitation in a changing climate will be undertaken. This will be of great value for improving flood estimation in small catchments based on event-based rainfall-runoff models or other estimation methods requiring rainfall.

Furthermore, a gridded version of the HBV model (1 x 1 km) is being developed. This will allow derivation of catchment characteristics from the GIS database and application to a sub-daily time-step. This would make the HBV model in general also usable for rainfall-runoff calculations in small catchments. It needs, however, to be investigated for which minimum catchment size a 1 x 1 km^2 gridded model can generate reasonable flood estimates. Furthermore, there are more than 15 parameters, which need to be calibrated for the catchment under consideration. Application of the model to ungauged sites further requires regional parameter estimation methods to be implemented.

An alternative model with less parameters has recently been developed by Skaugen & Onof (2013). In the so-called DDD (Distance Distribution Dynamics) model the dynamics of runoff are derived from the distribution of distances from points in the catchments to the nearest stream. Compared to the HBV-model, it has two completely new modules for soil-moisture accounting and runoff dynamics, while keeping the remaining modules of the HBV-model. Its main advantage is the reduction of the number of parameters to be calibrated from seven for these two modules in HBV-model to one, which reduces model structure uncertainty and improves model diagnostics. First results show the DDD-model to compare well with HBV-model, and in ongoing work, more experience with the model is being gained and further improvements of the river routing routine in particular are planed. As long as the needed input data (precipitation and temperature) are available in the required resolution, the DDD-model can be run with any time step, making it applicable also to small catchments.

The successful application of both models, the gridded HBV- as well as the DDD-model, to small ungauged catchments may, however, be limited by the spatial resolution of the GIS data needed for parameter estimation. The GIS database currently available at NVE has been derived from 1:50.000 maps.

5.2 Austria

The current guidelines for flood estimation in Austria (Lorenz *et al*., 2011) differentiate between small (< 10 km^2) and medium-sized (10-500 km^2) catchments in their recommendations of applicable methods. For small ungauged catchments, the use and comparison of several methods is recommended, including “Spendendiagramme” (a logarithmic diagram of the specific runoff for each return period based on all gauging stations along a water course or in a region; which permits interpolation of flood estimates for ungauged catchments in the same water course / region. An example can be seen in Figure 2), empirical formulas and precipitation-runoff modelling. The main difference between small and medium-sized catchments is the derivation of catchment characteristics. For medium-sized catchments, relevant characteristics can usually be derived from digital maps. For small catchments, the spatial resolution of the maps is not high enough, and catchment characteristics have to be determined through site visits and catchment mapping. A manual to estimate the surface-runoff-coefficient during local extreme precipitation events (convective) based on field mapping has been developed (Markart *et al*., 2004) and is recommended for use by the Austrian guidelines. Based on the derived catchment characteristics, regional extreme value analysis, regionalization methods or precipitation-runoff models can then be applied, depending on the purpose of the study. Estimated flood magnitudes, should in all cases, be compared to flood estimates in neighbouring small catchments with discharge observations. In general, they recommend the *Flood Frequency Hydrology* approach as summarized by Merz & Blöschl (2008). This approach stresses the importance of three types of information expansion:

temporal (by including information on historical flood events), spatial and causal, in addition to local flood frequency analysis. For small catchments, temporal and causal information expansion are particularly valuable, as long data series are rare in small catchments and their flood generating processes can differ considerably from other (larger) catchments in the region. However, temporal expansion is in many cases hampered by the lack of information.

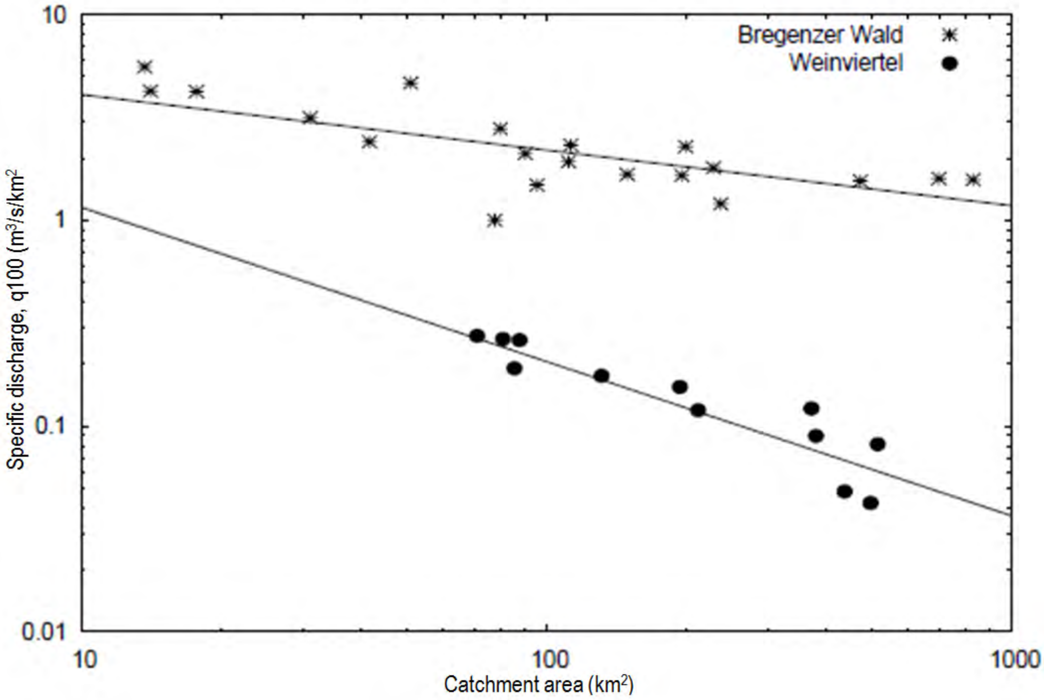

Figure 2 Specific discharge, *q100*, of the 100-year flood in two regions in Austria (after Merz, 2006).

Hemund *et al*. (2010) tested the combination of the catchment mapping manual and the Austrian precipitation-runoff model, ZEMOKOST, for its applicability to small catchments in Switzerland. They found the Austrian approach to be a simple and reliable method suitable for use in Switzerland. However, for catchment mapping a rate of 2-5 km^2 per day has to be expected.

In a comparative study, Hagen *et al*. (2007) evaluated around 40 mostly empirical, statistical methods for estimation of peak flows in small alpine catchments (torrents) in Austria. In the evaluation, both the quality of the result and suitability of the approach for practical application were considered. The evaluation was based on an analysis of the original literature, application to four catchments with good quality measurements (at least 20 years) and extensive catchment information, and the experience of practitioners. The four catchments were chosen to represent different catchment characteristics and varied in size from 0.13 to 17.8 km^2. Results were compared to the 150 year peak flow event and its 95% confidence interval, as calculated from the observations using the Gumble distribution. The considered empirical methods included 1) methods using *envelop curves*, based on catchment area only or with additional model parameters, 2) empirical methods based on one or more parameters, with and without precipitation input, 3) methods estimating the *runoff concentration* or *travel time* for surface- or channel runoff, 4) the standard *rational formula* (Chow, 1988) and modifications of it, and 5) *regionalized methods* based on continuous observed series in the region. Additionally, three deterministic methods were tested, which in contrast to the statistical, empirical methods, examine the relation between the cause and effect of precipitation and discharge in a catchment. Most of the methods are designed for use in ungauged catchments. However, the authors concluded that many of the empirical methods had been developed based on catchments of a particular region and that the catchment characteristics were frequently insufficiently described to allow transfer of the methods to other regions. The authors found accordingly, that methods which do not include parameters which describe catchment characteristics can in general not be recommended. Furthermore, it was found that empirical methods often suffer from the imprecise description of the physical interpretation of the parameters, making parameter estimation particularly subjective. Also, the choice of tabulated parameter values is often not wide enough to give sufficiently accurate estimations. These factors can all lead to severe under- or overestimation of flood magnitude. Compared to deterministic methods, these methods were found to typically be very robust against varying parameter values. The biggest advantage lies in their relatively easy and fast application. Methods in which the precipitation input is of main importance are often based on the assumption that a precipitation event of a specific return period leads to a peak flow event of the same return period. However, this is in most small catchments not the case. Furthermore, the assumption that during convective precipitation events the whole catchment is uniformly covered is for catchments exceeding 5 km^2, usually incorrect. This makes, for example, standard methods such as the rational formula less suited. For example, the rational formula was found to be valid only for catchments of a few square kilometres and smaller. The application of deterministic methods is more labour intensive and time consuming, since they require detailed field analysis of catchment characteristics. However, they have the advantage that the practitioner simultaneously gains a better understanding of the flood generating processes in the catchment.

The three *deterministic methods* were all so-called ‘black-box-models’: 1) an *empirical unit-hydrograph* model for a certain region of the Austrian Alps, 2) a *regionalised unit-hydrograph model* developed using IHW software, and 3) *the SCS-method using HEC-HMS* software (SCS and US-Army). The latter two were applied without observation based parameter calibration, in order to test the methods for application in ungauged catchments. Both methods were found to be very sensitive to the chosen precipitation input. This is problematic, as the estimation of the distribution of the precipitation event in space and time is often subject to high uncertainty. The results are furthermore strongly dependent on the experience and knowledge of the practitioner, as good estimates of the ground characteristics in terms of infiltration, storage and retention capacity of the catchment are essential. The standard procedures for the selection of parameter values were found to provide insufficient results. A more accurate estimate of the parameters, however, requires a detailed analysis of the catchment characteristics in the field, and makes the application of the methods therefore very labour intensive and time consuming. The SCS-method is generally poorly suited to forested areas and works best for agricultural areas, for which it was developed. It has now also been adapted for application in rural and urban areas, but is generally only valid for catchments up to 250 km^2.

The overall best performing method was the *regionalisation method GIUB*, developed in Switzerland. The method even performed best despite using regional parameters derived for the Swiss regions. This model was derived based on a large number of observations (time series from 540 stations and additionally around 200 observations of the highest peak flows in Swiss catchments below 200 km^2). Different growth curves are used for catchments smaller and larger than 100 km^2.

Overall, Hagen *et al*. (2007) conclude the Swiss method should be tested further by adaptation to local characteristics in the different Austrian regions, and the development of the more detailed deterministic methods should be further pursued making use of newly available GIS-based catchment information. The methods should however not include parameters which need information on catchment characteristics not commonly available. For many torrents in Austria, the consideration of sediment transport is crucial. Respective methods need to be further advanced as well and included in the hydrological models. Care has to be taken that the increased model detail does not lead to the expectation of unrealistically high accuracy.

5.3 France

Further work

In France, the *semi-continuous precipitation-runoff method*, SCHADEX (Paquet *et al*., 2006; 2013), is frequently applied for flood estimation with respect to dam safety assessments in France. However, in its current form, SCHADEX is dependent on observed discharge and precipitation data. An ongoing PhD-study at Electricité de France (EDF) aims to develop a new version, applicable for use in ungauged catchments. The suitability of the ungauged version for use in small catchments will, however, have to be evaluated.

5.4 Germany

The German guidelines (DWA, 2012) recommend the *Flood Frequency Hydrology* approach and the combination of all available information to improve the quality of the flood estimates. However, this does not mean that all kinds of information expansion and methods need to be applied. Instead, they give suggestions as to which methods to use under which conditions. For small catchments, they stress the importance of site visits and catchment mapping and that special care needs to be taken to identify land use changes.

5.5 New Zealand

The National Institute of Water and Atmospheric Research in New Zealand (NIWA) published an online map application (the Water Resources Explorer, WRENZ: http://wrenz.niwa.co.nz/webmodel/) in 2012. This allows the user to calculate the magnitude of floods with certain return periods (5, 10, 20, 50, 100 and 1000 year) for any watercourse in the country (NIWA, 2012). For small catchments (<30 km^2) it is advised to compare the estimation results from all three of the available methods. The first method is an index flood approach, where the *regional flood frequency growth curves* are derived based on small catchments less than 100 km^2 (Pearson, 1991), whereas the estimation of the *index flood* (mean flood, Q_m) is derived from contour maps of $Q_m/A^{0.8}$ based on catchments of varying size (McKerchar & Pearson, 1989). The second method is the *rational method* (see above), where the user is required to provide the correct runoff coefficient. The third method only gives Q_m directly from the *contour maps*, without calculating flood magnitudes for different return periods. The first two methods are typically more suited for small catchments than the third.

In the index flood approach used in New Zealand, homogeneous regions for the growth curves were defined by combining the grouping method by Wiltshire (1985) which splits the set of available catchments according to physical catchment characteristics, and L-moment statistics of the flood series (Hosking & Wallis, 1990). The considered catchment characteristics were basin area, the spatially averaged 24-h-rainfall with 5-year return period (I_{24}), a depth-weighted-macro-porosity index (*DWP*) as soil characteristic, a hydrogeology index (*H*) and the areally-weighted mean basin slope (*S*). Group homogeneity was assessed by the overall sum of squares of deviations of individual basin L-moment estimates (L-skewness and L-kurtosis) from their group record-length-weighted average points as well as two similar measures based on L-CV alone and L-CV and L-skewness. This resulted in a division into six groups based on I_{24} and *S* only. To each group the 5-parameter Wakeby distribution was fitted to generate dimensionless flood frequency growth curves.

McKerchar (1991) found that the index-flood estimates based on the contour maps of Q_m performed less well for smaller basins than for larger ones. However, an attempt to improve Q_m estimates for small basins using multiplicative regressions models based on catchment characteristics from small basins (<100 km^2) failed, and therefore use of the contour-map estimates is still recommended.

5.6 Lithuania

Three homogenous hydrologic regions have been identified in Lithuania. Two different approaches are recommended for estimation of spring flood magnitudes and their return periods in ungauged catchments. The approaches are not specific for small catchments, and are widely used. One of the approaches, called *reduction formula*, considers a special parameter to account for the different behaviour in small catchments. The reduction formula evaluates the reduction of peak flow with increasing catchment size. It further considers the influence of lakes and other water bodies, as well as wetlands and forests on peak flows (Sarauskiene & Kriauciuniene, 2012).

5.7 Poland

In the case of ungauged catchments, Polish guidelines for flood frequency analysis recommend two different methods for estimation of the *index flood* in catchments smaller and larger than 50 km^2. However, the same regional growth curves apply to all catchments irrespective of size (Strupczewski & Ozga-Zielinski, 2012). In catchments smaller than 50 km^2 the index flood is estimated based on the so called *rainfall formula*, which requires the following input parameters: dimensionless coefficient of the typical hydrograph shape, maximum module of specific discharge, runoff coefficient for peak flows, maximum daily rainfall for the 1% probability of exceedance, catchment area and a lake reduction factor.

5.8 Spain

In Spain, a *modification of the rational method* is used in ungauged catchments smaller than 50 km^2 (Mediero & Garrote, 2012). This modification was developed in Spain by Témez (1991) and takes advantage of the higher density of precipitation stations as compared to streamflow stations. The data input is the local frequency curve of annual maximum daily precipitation, which is estimated from observed data. Using the estimated rainfall for a given return period and the initial abstraction as given by the SCS Curve Number method, the runoff coefficient is calculated. The maximum mean rainfall intensity for a storm duration equal to the time of concentration is calculated based on the mean daily rainfall intensity and a coefficient which relates the mean 1-hourly to mean daily rainfall intensities. The modified rational method further considers catchment area and a uniformity coefficient, which takes into account runoff evolution during the storm.

5.9 Switzerland

The manual for peak flow estimation in Switzerland (Spreafico *et al*., 2003) distinguishes between small (< 10 km^2) and medium-sized (10-500 km^2) catchments. It also highlights the importance of field surveys for small catchments as the available maps resolutions are not detailed enough. To be of a sufficiently high resolution, maps of 1:5000 would be required. Furthermore, the value of single observations, historical material and the experience of (older) inhabitants in the region are stressed.

The required flood depends on the purpose of the study. Where the 1000-year event return period is required it is usually derived from an estimate of the 100-year event, for instance by multiplication with a safety factor of 1.3 – 1.5 for medium seized and larger catchments. However, due to the higher uncertainty of flood estimates of small catchments, a safety factor of up to 2 can be sensible.

Five different methods for flood estimation in ungauged catchments have been tested and applied to seven small catchments in Switzerland (Spreafico *et al*., 2003). The methods included: 1) an empirical method using *envelope curves*, which considers catchment area and the peak-flow-runoff coefficient, 2) a modified version of the *SCS-method*, 3) two different modifications of the *rational formula*, as well as the Clark-WSL method developed in 2001 and based a the simple conceptual precipitation-runoff model. For all methods, except envelope curves, precipitation intensities or amounts are needed. None of the tested methods were found to give sufficiently accurate estimates for all seven catchments. However, the method using envelope curves was generally found to overestimate giving an upper boundary for the estimates, whereas SCS-based method was found to underestimate, representing a lower boundary. It is therefore recommend using all five methods to assess the spread of possible flood estimates. If one of the remaining three methods returns results outside these boundary values, it should be seen as indication of a very difficult catchment. This result should, however, also be disregarded.

Another method, which can be used independent of catchment size (1-500 km^2) is the *HYDREG method* developed at the Ecole Polytechnique Fédérale de Lausanne (EPFL). It combines two different approaches typically valid for both small and large catchments. The method for small catchments is based on concentration time, whereas the method for large catchments follows the index flood approach. The two methods are linearly combined with weighting factors varying according to catchment size. Additionally, a so-called "boundary-regional-model" is included, which allows one to check and possibly improve flood estimates according to typical hydrological characteristics of a region. This method is useable for both gauged and ungauged catchments as long as they are included in the Swiss GIS-database, GESREAU.

5.10 UK

A range of methods have been recommended for use and applied to flood frequency estimation in small catchments in the UK. These methods include 'rules of thumb', local approaches, variants on standard techniques, and can all give widely differing results. Faulkner *et al.* (2012b) recently undertook a review of methods used in the UK, as part of Phase 1 of a project to improve estimation of flood peaks and hydrographs for small UK catchments. A summary of the methods used in the UK is provided below in chronological order of their date of publication, largely based upon the review of Falkner *et al.*, the original publications and other guidance. Of these, the Flood Studies Report (FSR) method and the Flood Estimation Handbook (FEH, which has superseded the FSR) are based on the most extensive research:

1. **Rational method**

   In the rational formula, flood peaks are estimated using the following equation:

   $Q = 0.278\ KIA$

   Where: K = runoff coefficient; I = rainfall intensity over the time of concentration; A = catchment area (km^2)

   The rational method has been used from time to time in small catchment studies. However, the Rational Method is not recommended for use in small lowland catchments (IH, 1999; Environment Agency, 2012) as it gives peak flows typically twice as large as those from the FEH rainfall-runoff method (IH, 1978b).

2. **Rational method: Transport and Road Research Laboratory (TRRL) LR 565 method**

   The LR 565 method (Young & Prudhoe, 1973) was developed to estimate flood flows on small natural catchments bordering motorways, and is a version of the rational method. The LR 565 method was developed using data from five gauges on four catchments, each on heavy clay, and ranging in size from 2.8 to 21.3 km^2. The LR 565 method is not as generally applicable or extensively founded as the FSR (Faulkner *et al*., 2012b), which was published shortly after.

3. Flood Studies Report (FSR)

The FSR (NERC, 1975) presents two methods for design flood estimation: (1) the statistical; and (2) the rainfall-runoff methods. In the statistical method, the index flood (the mean annual flood; QBAR) is derived from flood peak data or catchment descriptors (size, drainage density, a soil index, rainfall, and a lake index) and multiplied by a growth factor to estimate the flood peak with a return period of T years (Q_T). The FSR growth curves are fixed for a region (i.e. identical for large and small catchments) but can vary widely between regions. The growth factors are available in tables and are easy to apply, but quickly become dated and unable to incorporate the most recent (now c.40 years) of flood peak information, without re-calculating and publishing updates to the curves. The latest updates to the FSR growth curves are detailed in FSSR14 (IH, 1983), which details modifications for return periods greater than 100 years.

The rainfall-runoff method is based on the unit hydrograph, whose parameters are estimated from catchment characteristics. Inputs and initial conditions are selected to provide an estimate of Q_T. The FSR recommends that flood estimates derived from both methods should be improved where possible, using local data either from the site itself, or from a nearby catchment.

Prior to the publication of the FEH (see below; IH, 1999), the FSR was the most widely used flood estimation method in the UK. However, there is some concern over this methods applicability to small catchments as it was calibrated on data for catchments generally larger than 20km^2. Nevertheless, the FSR growth curves are still used by some practitioners, with the index flood estimated using alternative methods (e.g. IH 124; as recommended by Defra/Environment Agency, 2005) due to their ease of use.

4. Flood Studies Supplementary Report (FSSR) 6

The FSSR 6 (IH, 1978a) presented equations for QBAR, PR (percentage runoff) and T_p (time to peak) based on a subset of the original FSR catchments <20km^2. This report concluded that the results obtained for small catchments were no better than those obtained using the original FSR equations (Faulkner *et al*., 2012b). Later Marshall and Bayliss (1994) found the FSSR6 equation for T_p tends to overestimate response times.

5. Poots & Cochrane formula

The Poots and Cochrane (1979) formula for estimation of the index flood is an adaption of that published in the FSR for application to small (<20km^2) rural catchments, and especially those with heavy soils. The FSR offers a 6-parameter equation for estimation of QBAR, whereas Poots and Cochrane present a 3-parameter equation for estimation of the mean annual flood, based on catchment area, rainfall and a soil index, derived from small catchment data. Poots and Cochrane (1979) found that slightly better predictions were obtained for small catchments using their formula, as compared with the FSR.

6. **Modified Rational method**

The Modified Rational Method (National Water Council, 1981) was developed for sewer design. This method is not suitable for small rural catchments or greenfield runoff estimation as it was designed for sewered urban areas, but it may be appropriate to use it for estimation of low return period floods on very small catchments (up to ca. $0.2km^2$) that are completely developed and drained by sewers (Environment Agency, 2012).

7. ADAS 345

The Agricultural Development and Advisory Service (ADAS) Report 345 (ADAS, 1982) was developed for the design of field drainage pipe or culvert systems to protect crops from flood damage, and should only be considered for use in small rural sites with no formal drainage system (Environment Agency, 2012). In this approach, a graphical method (derived from the rational method) is used to estimate flow from land use, soil type and rainfall. ADAS 345 does not explicitly refer to return periods, but instead the choice of return period is made by the selection of a crop type from the charts, which correspond to return periods of 2, 5 and 10 years (see amendment in Faulkner *et al*., 2012b). This method was developed based on a small number of sites with limited records. The relationship between flow and return period is based on rainfall intensities derived in the 1960s (Bilham, 1962). This method is stated to not be suitable for catchments larger than ca. $0.3km^2$, but it was believed by former ADAS staff to be suitable for larger catchments (Faulkner *et al*., 2012a).

Although, ADAS 345 is only considered applicable for small rural sites with no formal drainage system, this approach was included in a review of flood frequency methods for small catchments by Faulkner *et al*. (2012b). They found this method tends to underestimate QMED (median annual maximum flood).

Highways Agency (2004) recommended IH 124 for use in catchments larger than $0.4km^2$ and ADAS 345 for smaller catchments, arguing that catchments smaller than $0.4km^2$ are unlikely to contain watercourses and, thus, IH 124 is not appropriate. The Environment Agency (2012) recently updated their guidance to recommend that ADAS 345 is not used for flood estimation in small catchments.

8. Institute of Hydrology Report 124 (IH 124) method

The IH 124 method (Marshall and Bayliss, 1994) has been widely used for flood estimation in small catchments. It presents a method for estimation of time to peak (Tp) and the mean annual flood (QBAR) in catchments $<25km^2$ based on catchment characteristics. It was developed by examining the response to rainfall in small catchments to help derive improved equations for flood estimation. The report particularly focuses on relatively permeable, dry and partly urbanised catchments. Out of all the small catchment methods available for the UK, IH 124 method is based on the most empirical data for catchments $<10km^2$ (Faulkner *et al*., 2012a), but was developed 20 years ago and thereby lacks the inclusion of recent flood peak data. For ease of application of this approach, QBAR is often combined with FSR regional growth curves, while Tp(0) estimates are often used together with the FEH design rainfall to obtain peak flow estimates.

Since its publication, IH 124 has often been recommended for use (e.g. Highways Agency, 2004; Defra/EA, 2005; Bamforth *et al*., 2006) particularly for catchments in the range 0.4/0.5 - 2km^2. For larger catchments, FEH methods have generally been recommended. For smaller catchments, either ADAS 345 (Highways Agency, 2004) or applying IH 124 with an area of 0.5km^2 and scaling the peak flows by catchment area (Defra/Environment Agency, 2005) has been recommended. These recommendations did not claim IH 124 gave more accurate results, but instead were aimed at meeting the pragmatic needs of the industry, given that it is simpler to apply and does not require specialist software. However, following a review of methods, Faulkner *et al.* (2012b) found that IH 124 tends to underestimate QMED and has a higher mean error than the FEH statistical method. The Environment Agency (2012) therefore recently updated their guidance recommending users to avoid IH 124 for flood estimation in small catchments.

9. FEH methods (both statistical and ReFH methods)

In the UK, the FEH methods (IH, 1999), and its subsequent updates (see below) are the most widely used methods for flood frequency estimation. These methods are structured around the same two approaches as the FSR, i.e.: (1) the statistical, and (2) the rainfall-runoff methods. The FEH statistical method, including recent updates (the improved statistical method, Kjeldsen *et al*., 2008) involves the analysis of annual maxima peak flow series to derive the index flood (QMED, i.e. median flood) and growth curve. The rainfall-runoff method is event based and provides a design flood hydrograph. The FEH rainfall-runoff method has now been superseded by the ReFH method (Kjeldsen *et al*., 2005; Kjeldsen, 2007). The FEH makes use of up-to-date datasets and digital catchment descriptors. In the UK, FEH methods tend to be the preferred choice in larger catchments where local impacts are averaged out.

The improved FEH statistical method comprises two stages (Kjeldsen *et al*., 2008). The first stage estimates the index flood, either from annual maxima observations or catchment descriptors. The formula for estimating the index flood (QMED) from catchment descriptors (denoted as cds) is:

$$QMED_{CDS} = 8.3602\ AREA^{0.8510}\ 0.1536^{(1000/SAAR)}\ FARL^{3.4451}\ 0.0460^{BFIHOST^{**}2}$$

Where: AREA = catchment area; SAAR = standard annual average rainfall; FARL = flood attenuation due to reservoirs and lakes; and BFIHOST = baseflow index derived from HOST soils data.

When undertaking flood frequency analysis for ungauged catchments, it is recommend to transfer data from a nearby suitable gauged (donor) catchment. This donor transfer aims to compensate for local flood controlling factors not represented in the lumped catchment descriptor equations, such as $QMED_{CDS}$ (above). However, it can be difficult to find a suitably small-sized, nearby donor catchment in practice. In the second step, a pooling group of ‘hydrologically similar’ catchments is created. Similarity is assessed with regard to catchment area, standard average rainfall, flood attenuation from reservoirs and lakes, and an index of the floodplain extent. The pooling group is used to derive the dimensionless growth curve from the Generalised Logistic distribution using the weighted averages of the second and third order L-moment ratios (L-CV and L-skew) for the pooling group. The flood frequency estimate for a site is estimated as the product of the index flood and the dimensionless growth curve. This statistical method has the advantage that growth curves are not fixed, instead being derived at the time they are needed from a pooling group of stations. As a result, this approach is therefore able to incorporate the latest flood peak data into flood frequency estimates.

The revitalised FSR/FEH rainfall runoff (ReFH) method uses an event based rainfall-runoff model to convert design storm events of a selected duration and return period, into a corresponding design flood event. Design storms are generated from the FEH CD-ROM (CEH, 2009) using the FEH depth-duration-frequency model (Faulkner, 1999). The ReFH model has four parameters which control hydrological losses: maximum soil capacity, time to peak, baseflow recharge and baseflow time-lag. These four parameters can also all be estimated using the catchment descriptors available from the FEH CD-ROM.

The FEH was developed to be applicable to a range of catchment sizes and types (Faulkner *et al.*, 2012b), and is applicable for use in small catchments >0.5km^2. For the recently updated versions of the FEH methods, this lower limit reflects the spatial resolution of the catchment descriptors which can be digitally extracted from the associated FEH CD-ROM (CEH, 2009), and not scale limitations of the modelling approach (Faulkner *et al.*, 2012b). It is only the original $QMED_{CDS}$ equation (IH, 1999) that is limited to use in catchments >0.5km^2, due to parameter values becoming physically unrealistic. However, given that gauged data from small catchments is sparse, and small catchments are not well represented in the calibration dataset, flood frequency estimates for small catchments are likely to have greater uncertainty.

10. **Area scaling**
    Although this is not a method in itself, an option sometimes used for the smallest catchments (e.g. <0.5km^2) is to consider a larger downstream catchment and scale the results by catchment area, taking into account any significant differences between the two catchments (e.g. soil type, land use, topography; Balkham *et al.*, 2010; Faulkner *et al.*, 2012b). However, this approach ignores rainfall areal reduction factors, changes in lag-time, and changes in both storm duration and intensity characteristics.

In the UK there has been various sources of guidance on the choice of method for small catchments (<20 – 25 km^2), but these tended not to be based on a scientific assessment of their accuracy. Faulkner *et al.* (2012b) recently performed an assessment of four of the most popular approaches: (1) FEH statistical method, (2) ReFH, (3) IH 124 and (4) ADAS 345, based on the ability of:

- various methods to estimate the index flood.
- the FEH methods to estimate flood frequencies for a range of return periods (T=2, 5, 30 and 100 years).

Results show there is a general tendency for all methods to underestimate the index flood. The FEH methods (FEH statistical and ReFH) generally perform better than the ADAS 345 and the IH124 methods. The performance of the methods appears to be strongly influenced by permeability and rainfall in the catchments. ReFH was found to frequently underestimate QMED in catchments with lower flows, and particularly permeable catchments. The IH 124 method was found to perform best when considering only catchments with low to moderate rainfall, closely followed by the FEH statistical method. The FEH statistical method growth curves show little spatial variation. With the ReFH method there is scope for variation, based on geographical location (as affected by the FEH rainfall growth curves) and the catchment properties in the ReFH model. However, it is difficult to be confident about the true value of return period flows, given records of limited length.

Faulkner *et al*. (2012b) concluded that the FEH methods (both statistical and ReFH methods) are applicable across a range of catchment sizes, and recommend these are used in preference to other available methods, except for highly permeable and possibly urban catchments (where the ReFH can be less reliable). They state that the continued recommendation of outdated methods, such as IH 124 and ADAS 345, is inappropriate. For catchments <0.5km^2, it is recommended that runoff estimates are derived from FEH methods applied to the nearest suitable catchment above 0.5km^2, (if this is representative of the study site) for which descriptors can be derived from the FEH CD-ROM and scaled down by the ratio of catchment areas. The Environment Agency (2012) recently updated their flood estimation guidelines for practitioners undertaking flood frequency assessments for sites in the UK, to take onboard these findings.

Future work

The recommendations presented by Faulkner *et al*. (2012b) represent interim guidance and are the result of Phase 1 of a project to improve estimation of flood peaks and hydrographs for small UK catchments. Phase 2 of the project will commence shortly, and aims to develop new simple methods for flood estimation. It is expected that a new software tool will be developed, which could form part of the CEH suite, and guidance on how to incorporate additional local information will be provided (Environment Agency, 2012). It is envisaged this will include the development of two new regression models which could predict L-moment ratios, and thus define the growth curve on small catchments using FEH catchment descriptors (Faulkner *et al*., 2012b). This would avoid the need to form pooling groups, given that gauged data from small catchments is sparse.

6 Non-stationarity and climate change

Non-stationarity

Non-stationarity in the hydroclimatological processes of a catchment can also cause flood characteristics to be non-stationary. Statistical flood frequency analysis based on observed discharge and flood time series can therefore result in unreliable estimations of current and future conditions. Excluding artificial intervention in a catchments (such as water abstractions, dams, culverts), non-stationarities can be caused by changes in climate as well as land cover (either man-made or as a consequence of climate change). As land cover changes in small catchments might occur fast (in terms of the percentage of catchment area affected) and more uniformly across the whole catchment than in larger catchments, it might be more important to specifically consider the influence of land cover changes on flood characteristics. However, this is not yet included in any of the reviewed flood estimation guidelines, which only consider a standard factor to account for the effect of climate change (see following paragraph).

Adaption to climate change – current approaches

As part of the COST Action ES0901 "European procedures for flood frequency estimation - FloodFreq", Madsen *et al.* (2013) recently reviewed methods applied in Europe for flood-frequency analysis in a changing environment. They found that all of the countries participating in the review, and consider climate change in their guidelines recommend multiplication of the current flood estimates for the current climate with a climate factor. With respect to urban drainage design, a climate factor is typically applied to the design rainfall. For both types of climate factors, the suggested values can differ between regions and return periods. They vary typically between 0% and 40% for return periods of 100 to 1000 years. For some regions in southern Germany increases of up to 50% and 75% are suggested for flood events with return periods of 50 and 2 years, respectively (Hennegriff et al., 2006). Interestingly, climate factors suggested for the design rainfall in Denmark increase with increasing return period, whereas the flood design climate factors in southern Germany decrease. In the UK increasing climate factors are given with respect to the considered projection period. Only in the UK and Norway are different climate factors for flood estimates suggested according to catchment size. The Norwegian guidelines suggest a standard climate factor (+20%) for all catchments smaller than 100 km^2. This reflects the current projected increase of local, short-term extreme precipitation throughout the country, and that smaller catchments are most vulnerable to this increase (Lawrence & Hisdal, 2011). For larger catchments the climate factors of 0%, 20% or 40% are suggested, depending on region and flood generating processes. With respect to dams (design, revalidation or planed upgrading) undertaking a sensitivity analysis to projected precipitation changes is suggested (Midttømme *et al.*, 2011).

In the UK, the current guidance (FCDPAG3 supplementary note; Defra/Environment Agency, 2006) is to add 20% to peak flow estimates, for all catchments >5 km^2, for any period between 2025 and 2015. For smaller catchments, FCDPAG3 recommends that peak rainfall intensities are increased by between 10 and 30% for the same period. However, in practice, peak flows in all catchments are increased by 20% in the preparation of flood management plans. Reynard *et al.* (2009) and Prudhomme *et al.* (2010) undertook an assessment of this guidance, and found that regional, rather than national guidelines for changes to peak flows due to climate change maybe more appropriate. The Environment Agency have identified the need to assess what methodologies and techniques could be used to incorporate current climate change projections, including the findings of Reynard *et al.* (2009) into flood frequency estimates (Heron & Chadderton, 2010), but this work is ongoing and new guidance is awaited.

In Austria, it is recommended to perform the flood estimation for the current climate only, as the impact of climate change is currently not quantifiable. Nevertheless, in the technical planning of reservoirs, dams or retention reservoirs, a climate enlargement should be added.

As Madsen *et al*. (2013) point out, there is still a gap between the need for climate change consideration as stipulated in the EU Floods Directive, current national guidelines and research. More focus should be given to the further development and use of non-stationary frequency models. They find Bayesian methods and the introduction of time-varying parameters into well-known extreme value models (e.g. the Generalised Extreme Value (GEV) distribution and the maximum likelihood methods) to be promising approaches. Dawdy *et al*. (2012) on the other hand, suggest basing flood frequency analysis on the physical processes which cause the floods. Topological and geometrical characteristics of channel networks could be used as basis, as these, in contrast to precipitation and runoff generation, do not change over long periods of time. An example of this approach would be the scaling theory of floods, which is also the basis for instance for the quantile regression method described in Section 4.2.

7 Conclusions

Most national guidelines recommend the comparison of several flood estimation methods, and this is particularly the case for ungauged catchments. The Austrian and German guidelines further recommend temporal, spatial and causal information expansion for all catchments, gauged and ungauged, according to the *Flood Frequency Hydrology* approach (Merz & Blöschl, 2008) to improve the quality of flood estimates. These countries, together with Switzerland, also stress also the importance of site visits and catchment mapping both to obtain data and to increase the reliability of such data for small catchments.

The definition of “small catchments” varies considerably between the various countries and studies included within this report. Instead of providing a general definition for small catchments, it is found preferable to specify the range of catchment areas for which each method is deemed applicable.

In practice, empirical approaches are the dominant flood estimation method used in small catchments. However, many of these methods cannot be recommended for application in other regions or to catchments with varying characteristics. The methods currently used or under development in Austria, Switzerland and the UK seem to offer promising approaches which could be adapted and tested for application in Norway. The ongoing work in the UK aims to improve the existing Flood Estimation Handbook (FEH) approach by developing two new regression models based on catchment characteristics to predict L-moment ratios and ultimately the growth curve specifically for small catchments. In Austria, the *Flood Frequency Hydrology* approach is recommended in addition to the Swiss *regionalisation method GIUB*, which also considers two different growth curves for catchments smaller and larger than 100 km^2. The advantage of the latter is, that it was derived based on a large number of observations, including both time series and individual spot gaugings. In Switzerland, the *HYDREG method* is further recommended. It can be used for catchments of 1-500 km^2 and combines two different approaches for small and large catchments using weighting factors which vary according to catchment size.

Additionally, Bayesian methods as well as the further development of rainfall-runoff models particularly for small catchments following for instance Grimaldi *et al*. (2012) should be considered. For the comparison of different flood frequency approaches and implementations, Renard *et al*. (2013) recently suggested a comparison framework which enables comparison of the estimated uncertainty. It has, however, to be remembered that, irrespective of the exact estimation procedure, the quality of the final flood estimate will depend largely on the quality and representativeness of the precipitation input (either at the event scale or as a continuous series) in case of rainfall-runoff models, and on the representativeness on the catchments used in regional approaches. When catchment characteristics are to be derived from GIS-databases, the spatial resolution of the underlying maps plays a major role. In particular for catchments <10 km^2, the accuracy and reliability of the catchment characteristics should be considered. For which, the Austrian manual developed by Markart *et al.* (2004) is likely to be useful.

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