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Guidelines for Design Flood Determination for Dams

2022 edition

Svenska kraftnät, Swedenergy and Svemin (2022)
Guidelines for Design Flood Determination for
Dams – 2022 edition

Cover photo: Dam on the Luleälven river. Photo: Vattenfall Vattenkraft AB. Distribution permit in accordance with Lantmäteriet's decision on case LM2021:047812.

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Svenska kraftnät
Swedenergy
Svemin

Preface

Determination of the design flood – the flood that a dam facility should be able to withstand and convey safely without being seriously damaged – is part of the work aiming to achieve satisfactory safety for dams.

This document is a revised edition of the Guidelines for Design Flood Determination for Dams that were issued in 1990 and previously revised in 2007 and 2015. In this edition the guidelines have been adapted to the Environmental Code, the Dam Safety Ordinance and consequence assessment regulations. The design flood requirements have been differentiated on a five-point scale depending on the severity of the consequences in the event of a dam failure. The previous scale and assessment criteria for differentiated requirements (Flood Design Categories I-III) are thus omitted. These changes mean that the new design flood requirements follow more closely the consequences of dam failure in flood situations.

Methods for calculating high to very extreme floods are described in the guidelines and remain unchanged in comparison to previous editions. Guidance on the handling of uncertainties in data and calculations, as well as effects that result from a changing climate, are provided in order to support the overall assessment of the flood for which a dam is to be dimensioned.

These guidelines are primarily directed to dam owners and consultants, but they also provide support for the relevant authorities. The principals are Svenska kraftnät, Swedenergy and Svemin. These organizations are working in partnership with SMHI – the Swedish Meteorological and Hydrological Institute - through what is known as the Flood Conference, with the task to follow up the application of the guidelines and propose changes, if necessary.

The guidelines were revised in 2021 at the initiative of the Flood Conference. A working group structured as follows was responsible for the revision: Kristoffer Hallberg (WSP Sverige AB, co-opted technical secretary), Maria Bartsch (Svenska kraftnät), Claes-Olof Brandesten (Vattenfall AB), Anders Frisk (co-opted Swedenergy), Jonas German (SMHI), Hans Häggström (Boliden AB), Peter Lindström (Skellefteälvens Vattenregleringsföretag), Agne Lärke (Fortum Generation AB) and Björn Norell (Vattenregleringsföretagen).

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Summary

The Swedish design flood guidelines were originally published by the Swedish Committee for Design Flood Determination (Flödeskommittén) in its final report in 1990. The design flood of a dam facility is the flood it should be able to withstand and convey safely without experiencing serious damage. This, the fourth revised edition of the guidelines, aligns to the Environmental Code, the Dam Safety Ordinance (2014:214) and the regulation on consequence assessment introduced in 2014. The design flood requirements are differentiated on the basis of the potential consequences of a dam failure under flood conditions.

The guidelines describe methods for calculating extreme floods which are consistent with the original guidelines. Method I is based on hydrological model simulations and can account for complex reservoir operation. In the simulations, extreme precipitation is assumed to coincide with a preceding wet autumn, intense snowmelt and saturated soils, rendering very extreme floods. Method II make use of frequency analysis based on historical data, hence the magnitude of derived extreme floods is associated with annual exceedance probability (AEP).

Consequences of dam failure are estimated according to categories stipulated in the Swedish Environmental Code. An overall assessment of the severity is expressed in five categories and determines the design flood requirement:

1. Very serious in terms of the impact across society; Design flood according to Method I.
2. Serious in terms of the impact across society; Design flood according to Method I, with some possibility for lower design criteria.
3. Moderate in terms of the impact across society; Design flood according to an event with an AEP of 1:200 by Method II.
4. Low in terms of impact across society but serious consequences to local private interests; Design flood according to an event with an AEP of 1:100 by Method II.
5. Low in terms of impact across society and low in terms of local private interests; The guidelines do not define design criteria for this category.

Furthermore, in categories 1 to 3, the dam should be able to convey at least the 1:100 AEP flood at full retention water level.

Calculation of the design flood rely on up-to-date and high-quality data. Uncertainties in the data and calculations should be taken into account, as should the impact of climate change. The owner’s decision and selection of the design flood must be documented and justified in the light of any uncertainty and the precautionary principle. The need for revision of the design flood is evaluated every ten years or after major changes to the design or function.

Sammanfattning

Flödeskommitténs riktlinjer för bestämning av dimensionerande flöden för dammanläggningar publicerades ursprungligen 1990 i Flödeskommitténs slutrapport. Dimensionerande flöde avser den vattenföring som en dammanläggning utan att skadas allvarligt ska kunna motstå och släppa förbi. I denna fjärde omarbetade utgåva har riktlinjerna anpassats till den samlade dammsäkerhetsreglering som infördes år 2014 genom ändringar i miljöbalken, förordning (2014:214) om dammsäkerhet och föreskrifter om konsekvensutredning. Konsekvenser av dammhaveri i samband med höga till mycket extrema flöden utgör grund för differentierade krav på dimensionerande flöde.

Riktlinjerna beskriver metoder att beräkna höga till mycket extrema flöden, vilka är oförändrade jämfört med de ursprungliga riktlinjerna. Beräkningsmetod I bygger på hydrologiska modellsimuleringar och kan ta hänsyn till komplexa vattenregleringsstrategier. I beräkningarna antas extrema nederbördsmängder samverka med effekterna av en snörik vinter med sen avsmältning, vilken även föregåtts av en nederbördsrik höst. Beräknade flöden är mycket extrema. Beräkningsmetod II avser statistisk frekvensanalys baserat på historiska data. Metoden ger storleken av extrema tillrinnande flöden och sannolikheten för deras förekomst.

Följder av ett dammhaveri bedöms för de skadekategorier som ligger till grund för dammsäkerhetsklassificering enligt miljöbalken. Krav på dimensionerande flöde utgår från en samlad bedömning av haverikonsekvensernas allvarlighetsgrad uttryckt på en femgradig skala:

1. Mycket stor betydelse från samhällelig synpunkt; Dimensionerande flöde enligt beräkningsmetod I.
2. Stor betydelse från samhällelig synpunkt; Dimensionerande flöde enligt beräkningsmetod I, med vissa möjligheter till lägre krav
3. Måttlig betydelse från samhällelig synpunkt; Dimensionerande flöde är ett flöde med årlig sannolikhet 1/200 enligt beräkningsmetod II.
4. Liten betydelse från samhällelig synpunkt men stor betydelse för enskilda intressen; Dimensionerande flöde är ett flöde med årlig sannolikhet 1/100 enligt beräkningsmetod II.
5. Liten betydelse från samhällelig synpunkt och liten betydelse för enskilda intressen; Riktlinjerna ställer inga krav på dimensionerande flöde.

För nivå 1–3 ställs även ett grundkrav om att vid dämningsgränsen kunna avbörda ett tillrinnande flöde med årlig sannolikhet 1/100.

Beräkning av dimensionerande flöde baseras på underlag vars aktualitet och kvalitet är av stor betydelse. Osäkerheter i underlag och beräkningar bör beaktas liksom effekter som följer av ett klimat i förändring. Ägarens beslut om dimensionerande flöde ska dokumenteras och motiveras mot bakgrund av förekommande osäkerheter och försiktighetsprincipen. Behovet av uppdatering av dimensionerande flöde prövas vart tionde år i en översyn anläggningsvis eller vattendragsvis samt vid större förändringar av dammens design eller funktion.

1 Introduction

In the spring of 1985, the Swedish hydropower industry and SMHI, the Swedish Meteorological and Hydrological Institute, decided to establish the Committee for Design Flood Determination, which was assigned the task of elaborating guidelines for the determination of design floods at hydropower and regulating dams. The committee, which included representatives of the hydropower industry and SMHI, investigated the design flood determination methods used both in Sweden and abroad. A system was devised for classification of dams with regard to the consequences of dam failure in connection with high floods, along with a new method for design flood determination. The results were stated in the final report of the Committee for Design Flood Determination (Flödeskommittén, 1990). Svenska Kraftverksföreningen and Statens Vattenfallsverk (now Swedenergy member companies) undertook[1] to comply with the guidelines and take active responsibility for their application.

A special consultation forum known as the Flood Conference (Flödeskonferensen) was established in 1991 between the principals of the guidelines. The task of the Flood Conference is to monitor the relevance of the guidelines and their progressive implementation and, if necessary, to propose amendments and additions. The guidelines have been applied to hydropower dams since 1990, resulting in implementation of dam safety measures at many facilities. There has been corresponding application of the guidelines in the mining industry since 2007. The guidelines have also been applied more widely; as a basis for inundation mapping along watercourses, for example.

The events that took place around Lake Vänern in 2000/2001 indicated that the guidelines cannot be applied categorically due to the particular conditions that prevail for this water system. The Committee for Review of the Guidelines for Design Flood Determination for Dams (Kommittén för komplettering av Flödeskommitténs riktlinjer) was formed in 2002 at the initiative of the Flood Conference and in cooperation with the mining industry. The committee submitted recommendations for application for large lakes with limited discharge capacity – such as Lake Vänern, application for small catchments and a general strategy for dealing with climate change (KFR, 2005), which were subsequently incorporated in the 2007 edition of the guidelines. More and more attention has subsequently been paid to climate change and climate adaptation, and the 2015 edition (Svenska kraftnät et al., 2015) included conclusions and recommendations from the Climate Committee (Klimatkommittén) (Svenska kraftnät et al., 2011) and related development projects on the application of climate scenarios in flood design.

The methodology of the Committee for Design Flood Determination has been presented in various international contexts, and application has been followed up and reported in several publications. Several extreme floods have also occurred in regulated rivers, including in the years 1995, 2000 and 2018. The overall assessment is that the methodology of the guidelines for hydrological model calculation describes the evolution of extreme flood situations in a realistic manner.

The guidelines are applied for the evaluation of existing dams and the planning of new dams. The guidelines are not intended to be used for determination of design floods for

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[1] Correspondence between the power companies, SMHI and the Government, October 1990

cofferdams or tailings facilities in closure or post-closure phase. The calculation methods and sensitivity analyses are deemed to be applicable, but the requirements do not include temporary structures or the long term perspectives presupposed in connection with the closure and post-closure phase of tailings facilities.

Regulated watercourses constitute systems that include dam facilities. In design flood determination, there is therefore a need for information exchange, a collective description of the system, coordination and collaboration between owners[2] of dams in the watercourse. Calculation data and results should be managed jointly and by watercourse. Appendix 3 illustrates the watercourse and system perspective in a generic calculation procedure for a system involving several dams.

A tailings facility is an integral part of the mine's concentration process for storing extractive waste and managing water. Tailings facilities generally have a small catchment area, often on a parity with the footprint of the facility itself. The water management for the mining operation, the treatment and storage of water, for example, takes place within the tailings facility.

Processes and operations that are a consequence of meteorological and hydrological conditions and events are analyzed and simulated when calculating design floods and water levels for dams with major failure consequences. The choice of regulation strategies, the design of dams and spillways, together with the conditions provided by the characteristics and climate of the catchment area, affect the origin and extent of extreme floods. In other words, both parameters that are possible and parameters that are not possible to control have an impact on the results of the calculations. It is therefore highly important to include changes regarding the handling of reservoirs or physical measures, such as reconstruction of dams and spillways. Dialogue between dam owners and the professionals calculating design floods is necessary in order to obtain high quality design data.

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[2] In the guidelines, the term "dam owners" is used synonymously with the terms "operator" and "maintenance accountable" to indicate the party that is obliged to maintain a dam. This is because the dam owner/operator is generally, but not always, the maintenance accountable for the dam.

2 Methodology for design flood determination

2.1 Basis

The design flood is the flood a dam facility should be able to withstand and convey safely without experiencing serious damage to the facility. The concept includes a sequence of inflows which, on account of their volume, result in a design discharge in conjunction with a design water level. In the calculations, the discharge capacity of a dam facility should only include documented capacity of the appurtenant structures that maintain such an operational status that they can be utilized when the need arises.

Design flood requirements for a dam facility are defined on the basis of the consequences that a dam failure could have in connection with high to very extreme floods, besides the consequences that these floods themselves entail (additional damage). If a dam facility consists of several dams, failure scenarios are selected and analyzed for the dams that could result in the most severe consequences.

Consequences are assessed in accordance with the 2014 dam safety regulation[3], with support of associated guidance (Svenska kraftnät, 2017). Scenarios, assumptions, calculation and assessment methods for impact assessments provided by RIDAS and GruvRIDAS (Swedenergy, 2019a; Svemin, 2021; Jewert et al., 2015; Midböe & Åstrand, 2017) should be applied for the analysis of failures and their consequences.

Two fundamentally different methods are used to calculate the design flood:

- Calculation method I make use of hydrological model technology (Bergström et al., 1992) and is used to calculate very extreme floods. This method takes into account complex water regulation strategies and is used for facilities with major failure consequences.
- Calculation method II make use of statistical frequency analysis (Coles, 2001) of inflow floods and is used to calculate extreme floods based on historical data.

The Environmental Code chapter 2, General rules of consideration etc., states that knowledge requirements and the burden of proof rest with the operator. The precautionary principle and the use of a reasonableness assessment are also expressed in the general rules of consideration. These are generally applied in matters relating to dam safety, and also when determining the design flood.

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[3] The Environmental Code, the Dam Safety Ordinance (2014:214) and Affärsverket svenska kraftnät's Regulations and General Advice on impact assessment in accordance with Section 2 of the Dam Safety Ordinance (2014:214)

2.2 Design flood

The consequences of dam failure in connection with high to very extreme floods form the basis for differentiated design flood requirements. The dam failure consequences are assessed for the different types of damage and losses that form the basis for dam safety classification in accordance with Chapter 11, Section 24 of the Environmental Code; loss of human life, disruption of electricity supply, destruction of infrastructure, destruction or disruption of activities essential to society, environmental damage, destruction of areas of national interest for cultural conservation and economic damage.

An overall assessment of the severity of the consequences is expressed on a five-point scale:

- Levels 1–3 refer to very major, major and moderate importance from a societal perspective and follow Svenska kraftnät's regulations[4] and guidance (Svenska kraftnät, 2017).
- Levels 4–5 refer to minor importance from a societal perspective together with major or minor importance for individual interests, in accordance with RIDAS Application Guidance (Swedenergy, 2019b).

The design flood requirements for dams with failure consequences according to levels 1–5 are presented in Table 1.

Besides these design flood requirements, the following basic requirements are set for levels 1–3:

- At the normal retention water level, the dam shall be able to discharge an inflow flood with an annual probability of 1:100.

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[4] Affärsverket svenska kraftnät's Regulations and General Advice on impact assessment in accordance with Section 2 of the Dam Safety Ordinance (2014:214)

Table 1. Flood design of dam facilities

Severity of the consequences, 1–5	Requirements	Consequences of dam failure in the case of high to very extreme floods
1. *Very major importance from a societal perspective.*	Design flood according to calculation method I. The discharge capacity at normal retention water level equals an inflow flood with an annual probability of 1:100.	May lead to a national crisis that affects many people and large parts of society, results in loss of human life and threatens basic assets and functions.
2. *Major importance from a societal perspective.*	Design flood according to calculation method I. A lower design flood can be selected if it is demonstrated* that the failure consequences are not of severity level 2 in the event of a flood according to calculation method I. However, the design flood must not be less than a flood with an annual probability of 1:500 according to calculation method II. The discharge capacity at normal retention water level equals an inflow flood with an annual probability of 1:100.	May lead to major regional and local consequences or disruptions, but the failure cannot lead to a national crisis. In this case, this relates primarily to loss of human life and/or consequences and disruptions that are extensive, extend throughout the region and will take a long time and be expensive to rectify.
3. *Moderate importance from a societal perspective.*	The design flood is a flood with an annual probability of 1:200 according to calculation method II. The discharge capacity at normal retention water level equals an inflow flood with an annual probability of 1:100.	May lead to significant local consequences or disruptions. This relates mainly to damage to local infrastructure, damage to property or environmental damage, or temporary disruptions. The risk of loss of human life is negligible.
4. *Minor importance from a societal perspective, but major importance for individual interests.*	The design flood is a flood with an annual probability of 1:100 according to calculation method II.	Cannot lead to significant local consequences or disruptions, but may lead to major damage for the dam owner or individual interests in terms of property and other assets.
5. *Minor importance from a societal perspective and minor importance for individual interests.*	Requirements concerning design flood are not defined in these guidelines.	Cannot lead to significant local consequences or disruptions, and cannot lead to major damage for the dam owner or individual interests in terms of property and other assets.

* It shall be shown that failure consequences for all floods in the range from the selected design flood up to flood according to calculation method I do not reach severity level 2.

Besides what is described in Table 1, a facility-specific reasonableness assessment between the degree of safety and the cost of achieving this may lead to a decision to design the facility for a higher or lower flood than the one calculated. This assessment should lead to greater consideration being given to the degree of safety to be achieved, and less consideration being given to the costs of this, the more serious the consequences of a dam failure.

The scope for moderation of the requirements for cost reasons is minimal for facilities where the consequences are of severity level 1. For facilities where the consequences are of severity level 2, there may be some scope to reduce the requirements if an existing installation does not fully meet the requirements. For such a facility, a measure that would only increase safety marginally cannot be considered reasonable if the cost of it is very high. For facilities where the consequences are of severity level 3, a higher flood is selected for the design and dimensioning of the facility if the added cost of this is reasonable in view of the increased safety this entails. For an existing facility where the consequences are of severity level 3 and do not fully meet the requirements, a measure that would increase safety only marginally cannot be considered reasonable if the costs involved are high.

The basic requirement concerning minimum discharge capacity at normal retention water level can be waived if this combination of inflow and water level in the reservoir cannot reasonably coincide. Furthermore, the basic requirement may be waived insofar as, with regard to the safety of the dam and consideration of the risk of flood surcharge damage along the rim of the reservoir, it is deemed sufficient that the said inflow can be discharged at a water level that surpasses the normal retention water level.

3 Calculation assumptions and data basis

3.1 General

Calculation and determination of the design flood is based on technical documentation in which topicality and quality are of great importance. This is why uncertainties and accuracy need to be managed and documented transparently. The documentation must be representative of the current conditions of the river system, in terms of both consequences in the event of dam failure and data for flood calculations.

According to Table 1, the requirements for design floods are based on the severity of the consequences of dam failure in the event of high to very extreme floods. Such scenarios may be included in the dam failure impact assessments that have been conducted for dam safety classification, or be available as working material that has not been reported within the framework of classification. In some cases, supplementary calculations may be needed for scenarios that are necessary in view of the requirements in Table 1.

The need to update the design flood should be examined every ten years, in review by dam facility or by watercourse, as well as in the event of major changes to the dam's design or function. The purpose is to check that the overall assessment of the consequences of a dam failure and the design flood calculations remain relevant. Such a check is ideally carried out prior to an overall dam safety assessment in accordance with paragraph 7 of the Dam Safety Ordinance (2014:214). It is also clearly linked to the dam failure impact assessment in accordance with paragraph 2 of the same ordinance, as scenarios in this are also of relevance for determination of design flood. The work can be coordinated for facilities in the same watercourse if the calculations have been carried out collectively using the same hydrological model.

Significant changes in hydrological or meteorological data, operating conditions and facility-specific aspects constitute grounds for reviewing design flood calculations. As the climate is changing, calculation assumptions should be reviewed regularly and sensitivity analyses carried out. Comparisons should be made between observations and calculated design flood if extreme events with significance for runoff occur.

The decision made by the owner about the design flood needs to be justified in each individual case in the light of uncertainty and the precautionary principle, which may involve a certain margin in relation to the calculations (see section 2.2).

All factors that affect dam safety must be taken into account in the ongoing dam safety work. Besides information on design floods and water levels, the data from design flood calculations contains many other details that can be used to increase hydrological understanding with respect to operation and dam safety. Flood dynamics data, for example, can be used in emergency management planning, action planning and scheduling of staffing at facilities. Calculation results can also be used when planning day-to-day operations and for prediction of the inflow and risks in connection with high to very extreme floods.

3.2 Uncertainty

There are several sources of uncertainty in both data and methodology that should be taken into account when planning and implementing the design flood calculations and when evaluating and applying the results. Sensitivity analyses are appropriate to support this, making it possible to assess calculation accuracy. Uncertainties must not prevent action being taken, whether it concerns the need for changed reservoir operation in the short term or the reconstruction of dams in the longer term.

Calculation assumptions and calculation results should be analyzed and appropriate sensitivity analyses carried out. The analyses that should be carried out depend on the characteristics of the facility in question and the quality of input data used in the calculation. The choice of time period on which the calculations are based is of great importance and should be given particular attention. Regardless of whether the design flood calculation is based on simulations with a hydrological model and/or statistical frequency analysis, there are sources of uncertainty (Andréasson et al., 2011a; Hallberg et al., 2016a) that should be taken into account when evaluating the results. Typical factors to consider are:

Calculation method I

- Hydrological model and model structure
- Data quality
- Calibration period
- Design snow cover period
- Design flood calculation period
- Calibration method
- Quality measures for calibration against peak values
- Quality measures for calibration against volume
- Description of regulation systems
- Discharge from natural lakes

Calculation method II

- Data selection
- Data period
- Data quality
- Frequency distribution
- Statistical goodness of fit
- Confidence interval
- Degree of extrapolation

For the use of hydrological models, data quality can be divided into simulation data quality and calibration data quality. Simulation data is primarily information about precipitation and temperature, which should reflect actual conditions well in terms of magnitude and geographical distribution. Calibration data primarily relates to inflow and water level with which model calculations are compared. Since inflow is generally calculated from water levels, discharge and reservoir tables, it is highly important that this data maintains a high level of precision, especially regarding flood situations and large spillway discharges.

Uncertainties in both calculation assumptions and calculation results should be taken into account in the overall assessment of the facility’s ability to store and discharge the flood for which the facility is to be designed.

3.3 Climate change

The climate is changing (IPCC, 2019; IPCC, 2021), which also entails changes in hydrological conditions. Changes in the occurrence, magnitude and nature of floods caused by thawing and precipitation (Arheimer & Lindström, 2015) can be expected within the technical service life of dams, which means that climate change should be taken into account in the actual decisions on design floods. The current climatological conditions for the calculation methods for design floods have been investigated (Bergström et al., 2008; German et al., 2014; Losjö et al., 2019) without prompting revision of the methodology.

The sensitivity of a river system to climate change should be analyzed by utilizing climate scenarios that describe both extensive and less extensive climate change (Hallberg et al., 2014). The methodology for this needs to be well documented and be supported by a scientific basis (Svenska kraftnät et al., 2011).

New conditions may lead to the need to revise design flood calculations. Uncertainties about how the climate is changing must however not hinder the implementation of measures necessary to enhance dam safety. Furthermore, these measures should where reasonable be designed so that flexibility and margins are created.

3.4 Flood attenuation

In design flood calculations for a dam facility, consideration must be given to realistic opportunities of attenuating the flood at the dam in question or at another upstream dam whose owners have undertaken to cooperate on flood attenuation. In the event that surcharge above the normal retention water level is in question, the reservoir should be drawn down to a normal water level as soon as possible in view of the safety of downstream dams and other downstream conditions.

Passive flood attenuation implies that reservoirs and lakes in a river system automatically limit and attenuate the flood on account of their respective discharge capacities. This applies to natural lakes and many regulation reservoirs. No active measures are taken to attenuate the flood, and thus full-capacity spill discharge from dam facilities is assumed. *Active flood attenuation* implies that there is storage volume available in one or more reservoirs that shall be actively made use of to reduce the downstream flow, by limiting the discharge to less than the maximum available capacity at a certain water level in the reservoir. As with passive flood attenuation, there must be reservoir storage volume available that can be utilized when extreme floods occur. This presupposes that the dam facilities have the ability to safely store water above the normal retention water level. The application of active flood attenuation is a management operation that requires careful analysis of the performance of the entire river system in a critical flood situation. Also, a discharge strategy is required, as robust as to be applied and has the intended effect even in cases where communications are down and information about the conditions in downstream reservoirs and facilities are failing. Active flood attenuation should be applied with caution and only when relatively large reservoir volumes can be made available with certainty in order to achieve the attenuating effect in a critical situation. The method also requires a well-rehearsed decision-making process that will work in critical situations.

4 Calculation method I

4.1 General

Calculation method I is used to calculate very extreme floods by combining flood-creating factors using hydrological modelling techniques, as described in this section. The overall effect of unfavorable conditions coinciding will be very extreme floods.

Calculation method I implies that a number of flood-creating factors, each of which is within the limits of what has been observed, are combined so as to produce the most critical overall effect at the studied site. The method is based on hydrological model simulations that describe the consequences of extremely large precipitation volumes falling under particularly unfavorable conditions. In the calculations, extreme precipitation is assumed to coincide with the effects of a snowy winter with late snowmelt, preceded by an autumn with heavy precipitation. The model calculations simulate the flows and water levels that occur when the actual observed precipitation is systematically replaced by a design precipitation sequence. Figure 1 provides a summarily description of the execution of design flood calculations.

The size of the design precipitation sequence has been established by analyzing observed extreme areal precipitation in different parts of Sweden. The method does not link the magnitude of the calculated flood with the probability of it occurring. Comparisons with frequency analysis indicate that floods calculated in this way correspond on average to an event with an annual probability lower than 1:10,000 (Lindström et al., 1993; Bergström et al., 2008).

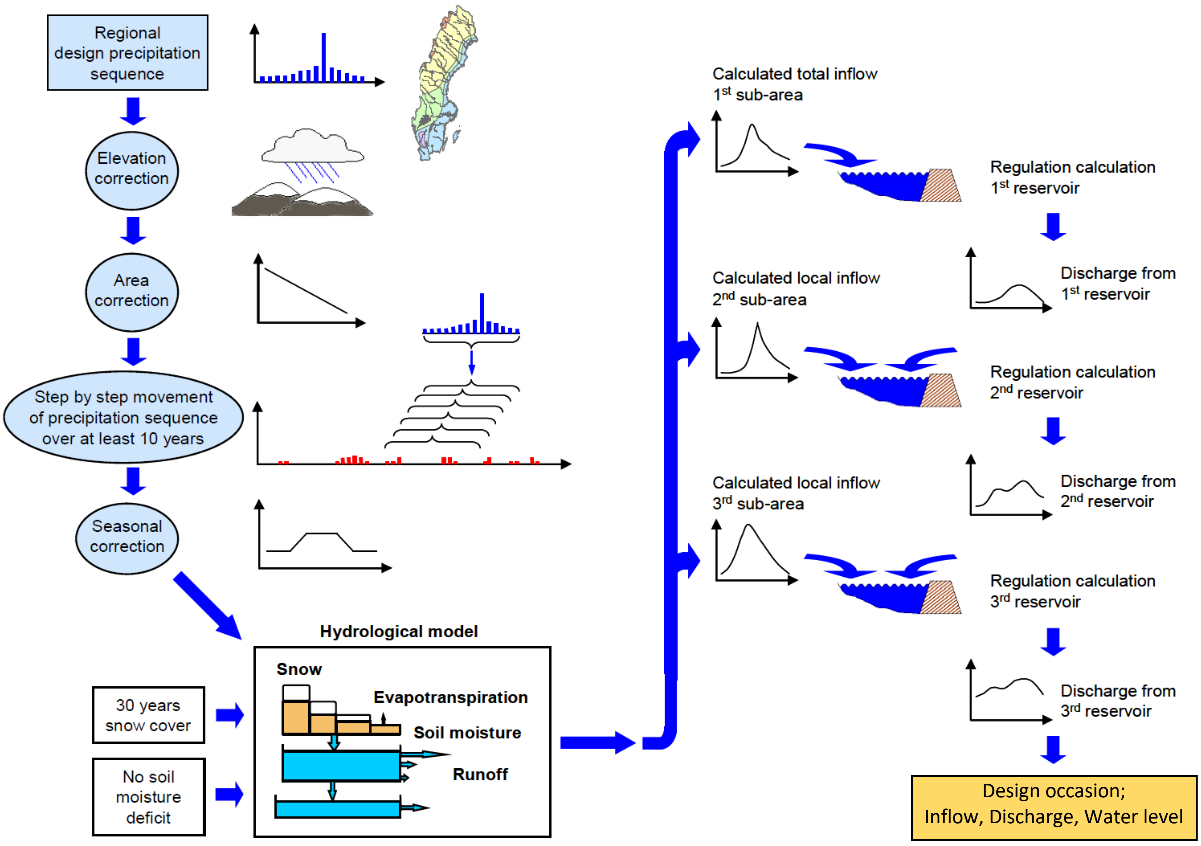

Figure 1. A principal drawing of the calculation of the design flood using calculation method I.

4.2 Application

Calculation method I can be applied to virtually any point in a river system for both unregulated and regulated conditions. The specified method can be used for catchment areas as small as 1 km^2 in size.

In most cases, this method can be applied even for large lakes with limited discharge capacity, and for facilities with discharge restrictions according to the court permits. However, an in-depth analysis is required for reservoirs that, like Lake Vänern, have special discharge conditions, including an upper limit for permitted discharge.

4.3 Model structure and model calibration

The hydrological model is adapted for calculations of high to very extreme floods through the structure and the degree of detail for how the catchment area is represented. The watercourse is divided into subareas for dams and lakes. Subareas are used for all incoming regulation reservoirs, large lakes and sections of river that may potentially function as reservoirs in a high-flood situation, or are otherwise so heterogeneous that they should constitute separate units. This division means that the local inflow, reservoir levels and discharge are calculated individually for each subarea. Subareas can also be created for locations where inflow data is available so as to enable calibration of the model at these points. It is appropriate to include results from hydraulic studies or hydrodynamic modelling of watercourses to describe head losses and provide a realistic – not too fast – response in the event of flood changes.

The hydrological model is calibrated against historical inflow series. Major emphasis should thus be placed on ensuring that the model reproduces high floods as accurately as possible. Good calibration of a hydrological model requires at least 10 years of data, and the period should include high floods originating from both thawing and rain. When modelling an entire river system, special emphasis should also be placed on the fact that the function of the entire river under extreme conditions is described in a realistic manner.

4.4 Discharge capacity

In the calculations, the discharge capacity of a dam includes documented capacity of the spillways that maintain such an operational status that they can be utilized when the need arises. Therefore, any discharge potential through turbines of hydro power stations or water recycled from tailings facilities to the mine’s concentration processes is not normally included as part of the discharge capacity. Consideration is given to possible head losses in headrace and tailrace channels and other obstructions that could affect the facility’s overall ability to convey water safely.

4.5 Design precipitation sequence

The build-up and development of the design flood is simulated by means of hydrological model technology, where the actual precipitation over 14 days is replaced by a design precipitation sequence.

These calculations are generally based on mean daily values, but for smaller catchment areas there is reason to study whether higher time resolution of day 9 in the design precipitation sequence may require for higher discharge capacity (KFR, 2005; German, et al., 2020; Johnell and German, 2021).

The precipitation sequence is specific to different regions in Sweden and is determined according to the division of regions in Figure 2. The design precipitation sequence for each region is provided in Table 2 and Figure 3.

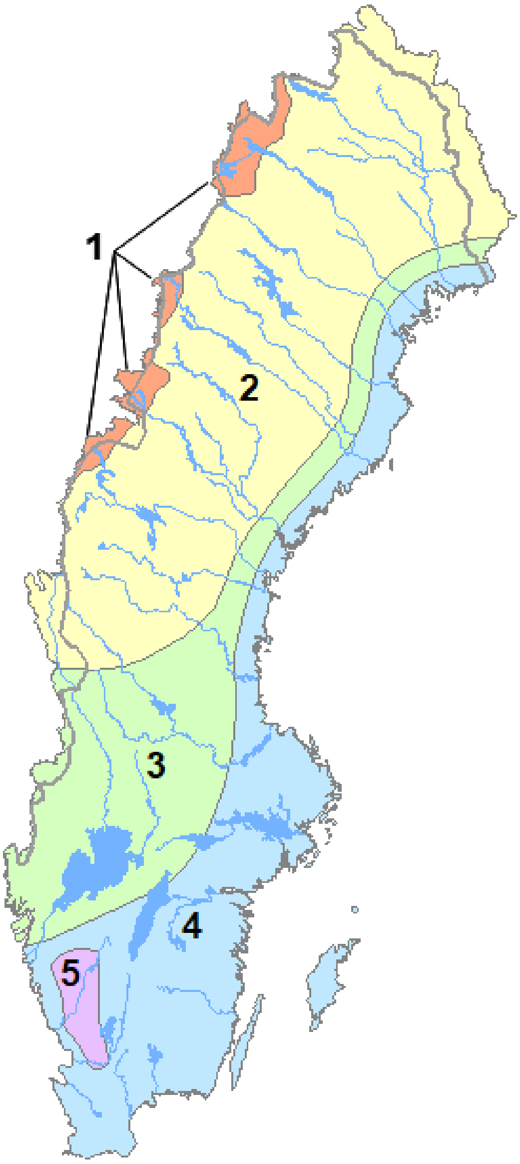

Figure 2. Regional division when selecting design precipitation sequence and seasonal correction.

Table 2. Design precipitation sequences for different regions in Sweden. The values refer to areal precipitation over 1000 km^2, specified in mm/24h. (The regional division is shown in Figure 2. See also the diagram in Figure 3.)

Day no.	**1**	2	3	4	5	6	7	8	9	10	11	12	13	14	**Total**
Region 1	6	6	6	6	6	10	10	40	120	25	10	10	6	6	267
Region 2	6	6	6	6	6	10	10	40	120	25	10	10	6	6	267
Region 3	6	6	6	6	6	10	10	40	135	25	10	10	6	6	282
Region 4	6	6	6	6	6	10	10	40	150	25	10	10	6	6	297
Region 5	8	8	8	8	8	10	15	55	150	30	15	10	8	8	341

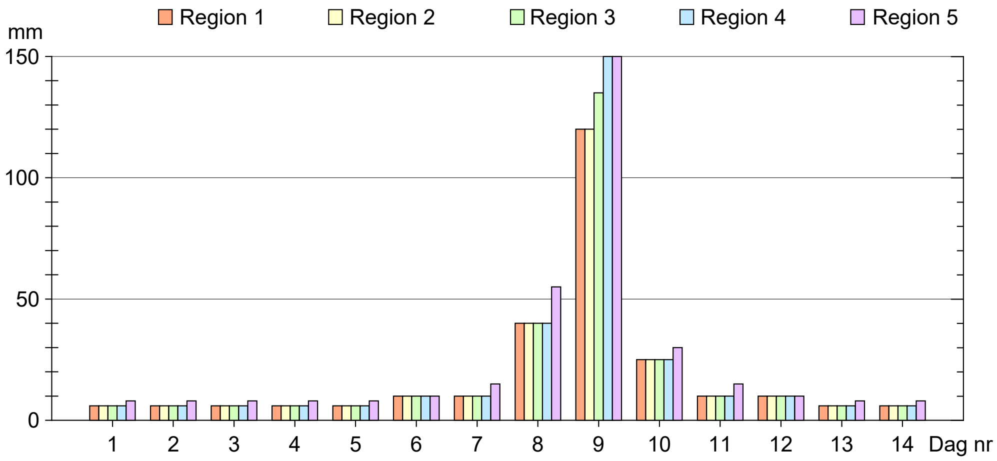

Figure 3. Design precipitation sequences for different regions in Sweden. The diagram refers to areal precipitation over 1000 km^2, specified in mm/24h.

For high altitude catchments, the fact that precipitation normally increases with altitude above sea level is taken into account. The increase is dependent on the geographical location, and therefore different corrections are applied for different catchment areas in Sweden (according to Table 3).

Table 3. Altitude correction of the precipitation sequences and reference level from which the correction is applied.

Catchment area	**Altitude correction (increase in precipitation sequence per 100 m above reference level)**	**Reference level (m a s l)**
Torneälven river to Indalsälven river	10%	500
Ljungan and Ljusnan rivers	10%	600
Dalälven river	5%	600
Klarälven river	5%	700

The precipitation sequence is also corrected for the size of the catchment area according to Equation 1 (illustrated in Figure 4).

$$\text{Areal correction factor} = 1.78 - 0.26 \cdot \log(\text{area of catchment area in km}^2) \quad \text{Eq. 1}$$

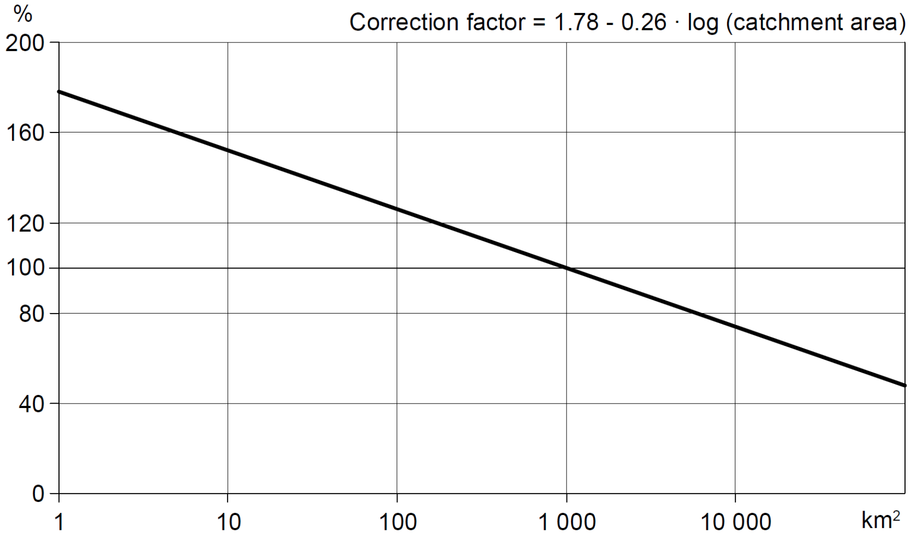

Figure 4. Correction of the design precipitation sequence against the size of the catchment area.

Furthermore, the precipitation sequence is corrected depending on the time of year at which the precipitation is assumed to fall. The seasonal correction takes place continuously during the step-by-step displacement of the precipitation sequence as described in section 4.9. Correction differs from region to region. In most regions, all precipitation values in the sequence are corrected according to a common curve. In region 5, however, the peak value of the sequence and the other values are corrected according to different curves. The seasonal correction is illustrated in Figure 5 and is performed as follows:

Region 1:
The values in the precipitation sequence according to Table 2, including its peak value, are assumed to be valid at 100% from 16 July to 31 March. The values are then reduced linearly to 50% on 30 April, after which a linear increase to 100% is assumed until 16 July.

Regions 2 – 4:
The values in the precipitation sequences according to Table 2, including their peak values, are assumed to be valid at 100% from 16 July to 15 August. The values are then reduced linearly to 50% on 16 November. The values are assumed to remain at 50% from 16 November to 30 April, after which a linear increase to 100% is assumed until 16 July.

Region 5:
The peak value of the precipitation sequence (day 9) is corrected according to the seasonal variation in regions 2 to 4, i.e. the peak value according to Table 2 is assumed to be valid at 100% from 16 July to 15 August. The value is then reduced linearly to 50% on 16 November. The value is assumed to remain at 50% from 16 November to 30

April, after which a linear increase to 100% is assumed until 16 July. Other values in the precipitation sequence are assumed to be valid at 100% from 16 July to 15 August. The values are then reduced linearly to 65% on 16 November. The values are assumed to remain at 65% from 16 November to 30 April, after which a linear increase to 100% is assumed until 16 July.

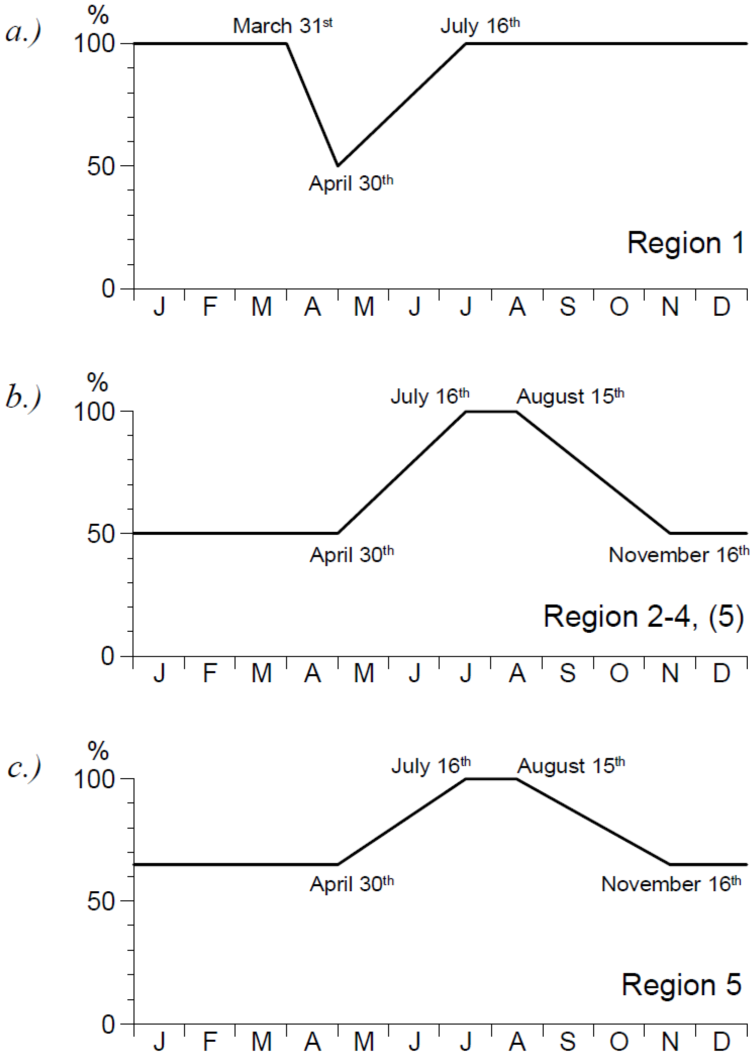

Figure 5. Seasonal correction of the design precipitation sequence.
a.) Correction of all sequence values in region 1.
b.) Correction of all sequence values in regions 2 to 4,
and of the peak value for the sequence (day 9) in region 5.
c.) Correction of all sequence values in region 5, except for the peak value.

4.6 Design snow cover

The design snow cover is the snow cover where the water content corresponds to an annual probability of 1:30 of occurring or being exceeded.

The time period for design snow cover is simulated using the hydrological model to calculate annual maximum values of the water content in the snow cover. These are used to calculate design snow cover using frequency analysis. The latest date on which the snow cover culminated during one of the years analyzed is determined. Design snow cover is given the same relative distribution between high-altitude zones and subareas as shown in the model calculation at the maximum snow cover during the simulation period.

It is advisable to use as long a period as possible for model calculation of the annual maximum snow cover.

4.7 Regulation strategy

In general, river systems with the possibility of regulation must describe water utilization in a realistic manner that neither overestimates nor underestimates the attenuation capacity of the watercourse.

Dams intended for the generation of hydroelectric power[5] apply the following regulation strategy:

- When the reservoir starts to fill, it is presumed that a minimum discharge is performed at a prescribed rate and that the production discharge is on-going at a rate considered reasonable for the event of a forecast predicting a strong spring flood. If predetermined discharge is or can be assumed to be prescribed, this must be taken into consideration.
- When the most intense precipitation is assumed to occur (from day 9 in the precipitation sequence and thereafter), it is presumed that the production discharge stops and that discharge can only take place via the dam’s spillways.
- Once the reservoirs included in the system have reached their respective normal retention water levels, which is presumed to have occurred by 1 August at the latest unless this is unreasonable with regard to the remaining snow cover, the reservoirs are assumed not to be lowered below the normal retention water level until the end of the critical flood period for the region.

When applied to tailings dams and dams intended for purposes other than the above, the regulation strategy is adapted to the special conditions that apply to these, including:

- When the most intense precipitation is assumed to occur (from day 9 in the precipitation sequence and thereafter), it is presumed that spill discharge can only take place via the facility’s appurtenant structures.
- If a water management plan specifies a maximum operational level in the reservoir, this may be taken into account. At the start of the calculation, the water level in the reservoir should be specified as the highest operating level, though as a minimum the water level corresponding to discharge of an inflow with an annual probability of 1:100. During the calculation, the water level in the reservoir is assumed not to be lowered below this level.
- If the reservoir contains anything other than water or is subject to emission conditions, this must be taken into account in the design of the regulation strategy, as this may reduce the possibility of discharge.

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[5] According to delimitation, chapter 11, Section 6 of the Environmental Code

4.8 Initial conditions

The calculation of the design flood starts when spring begins after a winter of heavy snow which is assumed to have been preceded by an autumn with heavy precipitation. The following conditions are therefore assumed at the start of the calculation:

- The existing reservoirs are lowered to levels deemed reasonable when a large spring flood is expected.
- The snow cover is set to the design snow cover.
- The flows in the river system are set to normal conditions antecedent to the spring flood.
- The entire catchment area has no ground moisture deficit.

The starting point for each year's simulation of floods is the day after the latest date at which the snow cover culminated, which was obtained when calculating the design snow cover.

4.9 Design flood calculation

Floods are simulated with the hydrological model over a period of representative climate conditions, but at least 10 years. In the model simulation, the actual measured precipitation over a 14-day period is replaced by the design precipitation sequence (Table 2) which is also corrected with respect to season, altitude above sea level and size of the catchment area. This is then shifted in time with the corresponding change in the seasonal correction, after which a new calculation is carried out. The displacement of the precipitation sequence and the corresponding flood calculation take place in steps of 24 hours at a time for all years included in the calculation period. The highest simulated water level in all these flood calculations gives the design occasion.

The temperature measured is reduced by 3°C during days 9 to 14 of the precipitation sequence during the period 1 January – 31 July so as to avoid unrealistic combinations of high precipitation and high temperature during the spring flood. In order to avoid unrealistically high 14-day precipitation volumes, caused by the design precipitation sequence ending up adjacent to observed high precipitation volumes, it is permitted to reduce observed precipitation values in connection with the sequence so that a continuous 14-day value does not exceed the total sum of the design precipitation sequence.

The calculations assume that the design precipitation sequence is added to the entire catchment area of the calculation point and is prefixed *total*. The design flood is also calculated, if necessary, for a local catchment area to the calculation point, and is then prefixed *local*. For a local calculation, the altitude and areal correction of the design precipitation sequence is applied, as well as the design snow cover that applies to the local area in question. The additional flood from other subareas is simulated in this case with the aid of observed climate data.

If both *total* and *local* calculations are performed for a facility, the design occasion is the one that gives the highest water level. If the watercourse system contains large natural lakes or regulation reservoirs that attenuate the flood, local calculation of the design flood for the area downstream of these is carried out.

For dam facilities where the discharge capacity is insufficient for the floods simulated, a calculation assumption is made of an overtopping of the dam if the reservoir level rises above the crest of the dam. Through this, the facility will convey the inflow without overestimating the flood attenuation in the calculation.

If it is concluded after the calculation has been completed that there is a need for adaptation measures for a facility, alternative measures need to be developed and the model updated with conditions that describe these. The measures may, for example, concern creating increased storage capacity by raising dams, increasing the discharge capacity by additional or rebuilt spillways and/or an altered discharge strategy. The calculation for the facility should then be repeated. Calculations of the design flood for downstream facilities may also need to be updated, unless the changes can be regarded as negligible.

Examples of the application of calculation method I are shown in Appendix 4.

5 Calculation method II

5.1 General

Extreme floods are calculated by means of statistical frequency analysis using calculation method II. In simple terms, the technique means that a theoretical distribution function is adapted to data material and then extrapolated to flood with the probability sought. This method provides the magnitude of extreme inflow floods together with their probability of occurrence. The calculation is based on the inflow to the reservoir in question, not the outflow from the reservoir. This prevents calculations from taking into account the effect of attenuation that is not always present. In view of the uncertainties that follow frequency analysis in extrapolation to extreme floods and the impact of water regulation, the use of alternative data and analyses will contribute to an overall picture that describes the potential for high to extreme inflows.

The probability of an extreme flood occurring or being exceeded during a single year is described with the event's annual probability, which is calculated using frequency analysis. Seen over longer periods of time, the probability of an extreme flood occurring is higher. Table 4 shows the probability of exceeding a flood with an annual probability of 1:100, 1:200 and 1:500 during different time periods. For example, an inflow flood with a magnitude corresponding to an annual probability of 1:200 over a period of 50 years has approximately 22% probability of occurring or being exceeded.

Table 4. The probability expressed as a percentage of inflow floods with an annual probability of 1:100, 1:200, and 1:500 occurring or being exceeded over a period of 10 years, 50 years and 100 years.

Period length	**Annual probability**		
	1:100	1:200	1:500
10 years	10%	5%	2%
50 years	39%	22%	10%
100 years	63%	39%	18%

5.2 Application, data and uncertainties

The analysis is primarily based on annual highest values of inflow calculated from observations to which a frequency distribution is adapted. Frequency distribution and the method for parameter estimation must be accepted for hydrological analysis and represent data well for high floods. Different dominant hydrological processes are implicitly described by using alternative data such as spring and autumn floods. Frequency analysis is used to calculate the inflow floods which correspond to an annual probability of 1:100, 1:200 and 1:500 respectively, insofar as these are called for by the requirements (see chapter 2). When calculating extreme floods with a very low annual probability of being exceeded, these are ideally compared with results from calculation method I.

The choice of time period affects the results, as well as the choice of frequency distribution and the method for estimating its parameters. It is appropriate to evaluate more than one distribution function and parameter estimation method and to perform the calculation for different time periods. The frequency analysis can be supplemented with calculation of confidence limits and statistical goodness of fit tests to estimate the uncertainty in the calculation.

It can be difficult to apply frequency analysis for watercourses that are strongly affected by regulation. Therefore, simulation with a hydrological model and standardized regulation (Hallberg et al., 2016a) for the extension in question may be an appropriate way of obtaining suitable data. This often allows longer time series to be used in the frequency analysis, and the flood response of the regulated watercourse can be assessed and analyzed in addition to observational data.

The inflow data series should be as long as possible, preferably more than 50 years. If such data is not available, it is necessary to perform the analysis for a shorter series. A shorter series increases uncertainty and places greater demands on the selected period being considered representative of the climate in the region.

If there is no inflow data for the site in question, calculations may be carried out on the basis of observations in another section of the watercourse in question, observations in nearby watercourses or model-calculated inflow.

If calculated extreme values are used to describe dynamic processes via what are known as inflow hydrographs, conservative approaches should be applied so as not to underestimate water volumes and durations. The application in these cases should be designed robustly in terms of possible time cycles as well, and not be limited to a single hydrograph or sequence of events.

Examples of application of calculation method II are shown in Appendix 5.

6 Implementation and documentation

6.1 Implementation, organization and competence

Design flood calculation is an extensive procedure consisting of many work steps, thus requiring special competence and quality assurance procedures.

The work requires hydrological expertise as well as knowledge of water regulation and dam safety. The calculations should be performed by personnel with experience of hydrological analysis and modelling, as well as good knowledge of water management for dams for hydropower and/or mining applications.

The work also requires procedures to be established to ensure the quality of the results. Quality assurance should involve routine checking of the calculations by someone other than the person who performed the calculations, documented internal control by the operator and a review by the dam owner.

Stringent demands are also placed on documentation of calculation assumptions and calculation results. Documentation is created to the extent necessary to show and support:

- Compliance with requirements – The documentation must show that the calculation follows applicable guidelines. Based on the documentation, an expert must be able to critically review the calculation and justifications for the assumptions made.
- Repeatability and traceability – It must be possible to recreate the calculation if necessary and clarify any reasons for differences in results between different calculation versions.
- Calculation assumptions – Calculation tools and data must be documented so that uncertainties can be assessed. When a hydrological model has been used, uncertainties and conditions for calibration must be documented so that it can be assessed whether there is reason to renew the calculations in connection with changes in the calculation assumptions.

The archiving method should provide an opportunity for access to factual data that can provide added value for dam safety work, e.g. data such as calculation variants with different conditions or assumptions.

6.2 Modeler´s documentation

Calculations by method I should be documented in a way making it is easy to survey the calculation assumptions and to reproduce previous versions of the model set-up. Comparisons of results between different versions should be made possible by appropriate naming of input data files and result files, for example. If both total and local design flood calculations have been performed, the calculation cases that do not result in the design occasion should also be documented. In order to clarify the calculations performed and enable assessment of the quality of the work, the documentation should be structured in a clear manner and contain the following points:

1. Facility data
2. Regulation details

3. Model details
    3.1. Subareas
4. Model calibration
    4.1. Calibration period for relevant subareas
    4.2. Model calibration
    4.3. Application of parameters for non-calibrated areas
    4.4. Adaptations for the river system – time shifts between subareas
    4.5. Ability to reproduce historical floods in the watercourse
5. Design flood calculations (total and local calculation)
    5.1. Area characteristics
    5.2. Snow calculation
    5.3. Precipitation sequence
    5.4. Design data
    5.5. Design flood results (spring and autumn occasion)
6. Sensitivity analysis
    6.1. Sensitivity analysis for a changing climate
    6.2. Analysis of sensitivity in input data and calculation assumptions
7. Modeler
8. Administration/archiving

Examples of documentation are shown in Appendix 4.

Calculations by method II should be documented in a way to make it is easy to survey the calculation assumptions and so that the calculations can be reproduced. Besides the hydrological data that serves as a basis for the calculations, the selection criterion and time period for the data are documented, along with technical aspects related to frequency analysis such as choice of distribution functions and associated method for parameter estimation. The frequency analysis should be presented graphically. In order to clarify the calculations performed and enable assessment of the quality of the work, the documentation should be structured in a clear manner and contain the following points:

1. General information
2. Frequency analysis
3. Sensitivity analysis and statistical goodness of fit
4. Modeler
5. Administration/archiving

If the calculations are based entirely or partly on observations from another point, or if a model-calculated inflow has been used, this must be stated clearly. The documentation must then include which measurement station(s) has/have been used and how they have been analyzed, as well as reasons as to why these have been selected. In the case of model-calculated inflow, assumptions and criteria for the model should be documented and also archived with the calculations.

Examples of documentation are shown in Appendix 5.

6.3 Dam owner’s documentation

The dam owner checks and documents the calculation and determination of the design flood. Decisions concerning design flood, design discharge capacity and design water level are accompanied by justifications.

The Dam Safety Ordinance (2014:214) defines requirements for whoever is obliged to maintain a dam that is classified in dam safety category A, B or C in accordance with the Environmental Code. The requirement to establish and work according to a safety management system[6] requires a systematic approach to information management (Svenska kraftnät, 2020b). The dam safety guidelines, RIDAS (Swedenergy, 2019a), provides guidance on good practice for managing facility information.

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[6] This provision does not apply to tailings dams that constitute a high-risk facility in accordance with Section 10 of the Ordinance concerning extractive waste (2013:319). For these, corresponding requirements are instead defined in the aforementioned ordinance, and supplementary guidance is provided in GruvRIDAS (2021).

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Appendix 1 Terminology

Term	Explanation
Discharge	Diversion of water, ice and debris from a reservoir to its downstream area or outflow from a natural lake.
Appurtenant structure	The structure and related equipment which discharge and lead water from a reservoir to the dam facility's downstream area, such as a spillway, outlet or pumping system.
Discharge capacity	For dam facilities, documented discharge capacity refers to the appurtenant structures that maintain such an operational status that they can be readily utilised when the need arises. Production discharge is normally not included. For natural lakes, this refers to the capacity that follows from the function of the lake outlet.
Dam	A water facility whose purpose is to retain or avert water or mixtures of water and other materials.[7]
Dam facility	A collective term for one or more dams which together retain a reservoir and/or protect lower-lying areas from flooding. This term also includes dams that regulate water bodies adjacent to the reservoir[8].
Dam failure	An uncontrolled outflow of the water or mixture of water and other material that the dam is intended to retain or avert[8].
Design flood	The design flood of a dam facility is the flood the dam should be able to withstand and convey safely without experiencing serious damage.
Design snow cover	The snow cover, with an annual probability of 1:30 of occurring or being exceeded, used in the application of calculation method I.
Design occasion	The date resulting in the highest simulated water level with calculation method I. Occasions before/after 1 August are often distinguished, which are then referred to as spring/autumn occasions
Design discharge	The highest discharge in connection with the design occasion when applying calculation method I
Design inflow	Maximum inflow in connection with the design occasion when applying calculation method I
Design water level	Maximum water level in connection with the design occasion when applying calculation method I

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[7] Chapter 11 of the Environmental Code

[8] The Environmental Code, the Dam Safety Ordinance (2014:214) and Affärsverket svenska kraftnät's Regulations and General Advice on impact assessment in accordance with Section 2 of the Dam Safety Ordinance (2014:214)

High flow Very high flow Extreme flood Very extreme flood	Flow within the size range corresponding to annual probability 1:5 – 1:25 of occurring. Flow within the size range corresponding to annual probability 1:25 – 1:100 of occurring. Flow exceeding the size corresponding to the annual probability 1:100 of occurring, but below a flood that follows from calculation method I. Flood of a magnitude resulting from calculation method I or above.
Reservoir	The amount of water, or mixtures of water and other materials, retained by one or more dams[9].
Spill discharge	Diversion of water from a reservoir without making use of it for other purposes such as electricity generation.
Discharge	Diversion of water from a reservoir, which may include both discharge through power stations (production discharge) and discharge through appurtenant structures (spill discharge).
Water facility	A facility which has been created through a water operation, together with control equipment belonging to such an installation[8].
Annual probability	Mathematically calculated probability or frequency over a certain time period, which links a flood magnitude and its occurrence. The concept indicates the annual probability of a flood of a certain magnitude occurring or being exceeded (*also known as Annual Exceedance Probability).*

Appendix 2 Background and history

Design in the past – development of the 1990 guidelines

Dams have been constructed in Sweden for several centuries, which has developed knowledge and experience in dam construction technology for Nordic conditions. Rules and common guidelines for design and dimensioning of dams have been introduced in recent decades, while it was previously mainly the operator who decided how dams were constructed. Statens Vattenfallsverk, Vattenfall, developed various instructions for the design and construction of dams early on which were also used by other companies. The hydropower expansion culminated in the 1950s and 1960s, and since the late 1970s there has been no major new exploitation of hydropower (Svenska kraftnät, 2020a). During the expansion period, there was technical expertise and a hydraulic laboratory at the Royal Institute of Technology, but there were no established rules for calculating design floods. Simple rules of thumb were often used, such as a safety margin of 10–20% to the highest observed flood at the site (Flödeskommittén, 1990).

Extreme floods and flooding in the early 1980s prompted the formation of the Committee for Design Flood Determination, which was tasked with elaborating guidelines for determination of design floods for hydropower dams and seasonal storage reservoirs. The committee studied nationally and internationally applicable design flood determination methods, and SMHI conducted studies of observed riverflows during floods and extreme areal precipitation in Sweden. It was concluded that the most important flood-creating factors to consider are precipitation, thawing, ground moisture deficit and available reservoir storage volume, and it was suggested that the resulting consequences in the event of a dam failure would constitute a basis for differentiated design flood requirements. For this purpose, a consequence-based classification system was created for dams with division into risk classes I and II (later flood design categories I and II).

The committee developed a new method for determining design floods that is based on hydrological model technology and describes the consequences of extremely large precipitation volumes, a design precipitation sequence, falling under particularly unfavorable conditions. The size of the design precipitation sequence was determined by analysis of observed extreme precipitation in different parts of Sweden, mainly on observations between 1881 and 1988 (Vedin and Eriksson, 1988). For dams of a lower risk class (with less serious consequences in the event of a dam failure), it was proposed that the design flood should be calculated using frequency analysis. According to the committee, the most important reason for limiting the application of frequency analysis was the high uncertainty that follows when extrapolating to floods with long recurrence times (flood size with low annual probability of being exceeded).

The method of superimposing unusual flood-creating factors contrasted strongly with the prevailing international design methods, and after the publication of the Committee for Design Flood Determination's guidelines, the methodology was presented in international journals (Norstedt et al., 1992; Bergström et al., 1992; Lindström and Harlin 1992) and at scientific conferences.

2007 guidelines – changes since 1990

The Committee for Review of the Guidelines for Design Flood Determination for Dams (Kommittén för komplettering av Flödeskommitténs riktlinjer, KFR) was formed in 2002 at the initiative of the Flood Conference and in cooperation with the mining industry. The committee was tasked with reviewing the guidelines for large lakes with limited discharge capacity, as well as tailings dams and other dams with small catchment areas. The committee was also tasked with discussing an overall strategy for how the climate issue should be handled. The committee's work was presented in a report published in 2005 (KFR, 2005).

Possible changes in extreme floods in Sweden had been studied (Bergström et al., 2001; Andréasson et al., 2004). The results showed that global warming will probably lead to reduced spring floods in Sweden, but at the same time an increasing risk of rainfall induced floods during summer, autumn and winter. This change is due to the fact that winters are expected to be shorter and less stable, and that precipitation is expected to increase, primarily in western and northern Sweden.

Svenska kraftnät, Swedenergy and SveMin jointly appointed KFR to be responsible for producing a new edition of the guidelines, which was published in 2007 (Svenska kraftnät et al., 2007) and thus replaced the guidelines in the Committee for Design Flood Determination's final report and the subsequent additions. The new, shorter design meant that it was not possible to include all background material. The work on the new edition was also supported by performed follow-up on the guidelines (Lindström et al., 1993; Brandesten et al., 2006) and observed extreme floods in regulated rivers, for example in the year 1995 and 2000. The overall assessment is that the guidelines describe the build-up and course of extreme floods in a realistic manner.

The new edition in 2007 incorporated the conclusions in KFR's 2005 report. This meant that the application of the guidelines in view of changes in the future climate was addressed. However, the methods in the guidelines were not revised and the meaning of the original guidelines with amendments remained essentially unchanged, with the following exceptions:

- The guidelines' validity for design according to flood design category I was extended to cover catchment areas down to a size of 1 km^2. This meant that the application of the guidelines to the mining industry's dams, which often have very small catchment areas, was clarified. It was further clarified that the guidelines do not apply for as long a time perspective as may be relevant for the closure or post-closure phase for certain tailings facilities.
- The new edition states that design calculation in flood design category I should be based on climate data representative of the conditions in the area, while the Committee for Design Flood Determination's final report stated that the climate data for the last available years is used.
- The geographical regions for the validity of the guidelines were extended to cover Sweden's entire catchment area, i.e. parts of Norway and Finland as well.

- A reservation is made for the applicability of the guidelines for Lake Vänern and any other cases similar to Lake Vänern.
- No distinction is made between existing and new dams in terms of adaptation of dams in flood design category II to a flood greater than the 100-year inflow determined by cost-benefit analysis (inflow flood of size corresponding to an annual probability of 1:100 of occurring or being exceeded).
- The instructions contained in the Committee for Design Flood Determination's final report on temporary dams/cofferdams were not included in the new edition, as these instructions were not considered sufficiently thorough.

Furthermore, the term *risk class*, which was used in the original guidelines, was replaced by the term *flood design category*. In addition, there were sections concerning documentation, competence, quality control and application examples.

2015 guidelines – changes since 2007

In 2008, the Committee for Design Floods for Dams in a Climate Change Perspective (Kommittén för dimensionerande flöden för dammar i ett klimatförändringsperspektiv, the Climate Committee) was formed through an agreement between Svenska kraftnät, Swedenergy, SveMin and SMHI. The committee analyzed and evaluated the importance of the climate issue for dam safety between 2008 and 2011 and compiled a guide for dam owners for the implementation of future design calculations for dams in a changing climate (Svenska kraftnät et al., 2011). This work was carried out in close collaboration with a project for the development of methodology for utilizing climate scenarios in design flood calculations (Andréasson et al., 2011b). The method for adaptation of the calculation methods to incorporate climate change was then presented at international conferences (Bergström et al., 2012; Bergström and Andréasson, 2013; Andréasson et al., 2013; Hallberg et al., 2016b). The results show that the methodology jointly developed by the power industry, Svenska kraftnät and SMHI produces good results.

In 2010–2011, a study was also carried out of different detailed uncertainties in design flood calculations (Andréasson et al., 2011a). Among other things, it was concluded that there are reasons to review calculations performed with older model versions and that it is important to take climate uncertainty into account in future calculations.

In 2011, the Flood Conference appointed a working group tasked with preparing the issue of the description of dam flood design and margins from a watercourse perspective. In 2013, this work was expanded to conduct a review of the guidelines as a whole, with the main focus on clarification of working methods and documentation of design flood calculations. The aim was also to include other results and experiences gained through the work of the Climate Committee and others. As a basis for the review, the Flood Conference also took the initiative to conduct a follow-up of the application of the guidelines up to and including 2013 (German et al., 2014), based on the results of the previous follow-up (Brandesten et al., 2006) and thereafter raised questions. Precipitation observations after 1990 largely confirmed the original analysis, although variations in the occurrence of extreme rain were observed (Bergström et al., 2008; Wern 2012).

The changes in the 2015 edition are summarized as follows:

- The conclusions and recommendations of the Climate Committee and related development projects on the use of climate scenarios for design flood calculations in a changing climate were incorporated.
- The importance of coordination and continuous exchange of information between the dam owners in a water system is emphasized, and that calculations for dams in a watercourse should be managed in a common model.
- Flood design category III was introduced (explicitly) for those facilities that fall outside of categories I and II, but requirements for discharge capacity are not specified in the guidelines.
- The basic rule – that it shall be possible to discharge the 100-year inflow at the normal retention water level for dams in flood design categories I and II – was reformulated in view of the fact that this combination of inflow and water level in the reservoir may in practice be considered to be excluded at certain facilities.
- The need for suitable calculation assumptions for the storage and discharge capacity of upstream dams was clarified in view of the fact that flood attenuation should not be overestimated, as this can affect the design flood and water level for downstream dams.
- The value of good documentation and quality assurance of design flood calculations is emphasized. Descriptions of documentation of calculations were developed, as well as application examples and explanations of items included in the documentation, and were incorporated in appendices with calculation examples.

2022 guidelines – changes since 2015

In the 2022 edition, the guidelines have undergone extensive revision in relation to the 2015 edition. The guidelines have been adapted to link with the overall dam safety regulation that came into force in 2014, and the terminology has been modernized. The division into chapters is new, appendices have been restructured and appendices for terminology and history have been added.

The main changes are summarized as follows:

- The term “design flood” is generally used to describe the flood that a dam facility should be able to withstand and convey safely without being seriously damaged.
- The design flood requirements are based on the consequences of dam failure in connection with high to very extreme floods, which are assessed for the types pf damage and losses that form the basis for dam safety classification in accordance with Chapter 11, paragraph 24 of the Environmental Code.
- The requirements are differentiated on a five-point scale, which means that the requirements follow the consequences of dam failure more closely in flood situations. The changed requirements mean easing in some cases, but tightening in others. The previous scale and assessment criteria for differentiated requirements (Flood Design Categories I-III) are thus omitted.
- The severity of the consequences of dam failures in the event of high to very extreme floods is assessed in accordance with Svenska kraftnät’s regulations and

guidance for impact assessment, which is supplemented in parts by Swedenergy's dam safety guidelines.

- The terminology for high to very extreme discharge volumes has been modernized. The frequency or occurrence of high to extreme floods is described statistically as annual probability instead of recurrence time.
- The guidelines describe two different methods for calculating the design flood; calculation methods I and II. In terms of content, these methods are essentially unchanged compared with previous editions of the guidelines.
- Calculation method I (hydrological model technology) has been clarified with respect to the design of the regulation strategy for tailings dams and dams intended for purposes other than the generation of hydropower.
- Calculation method II (frequency analysis) permits the use of data from hydrological models.
- The dam owner's documentation of the design flood should be included as part of the systematic information management, in line with the existing safety management system.
- The need for revision of the design flood is tested every ten years on a facility by facility basis or by watercourse as well as in the event of major changes in the dam's design or function.
- Wind speeds for determining wind effects have been removed from the guidelines.

Appendix 3 Basic calculation procedure for a river system

The following example shows how design flood calculations can be carried out for different parts of a river system, which includes a number of dams and regulation reservoirs, as well as natural lakes and river sections. The structure of the river system is illustrated schematically in *Figure 6*.

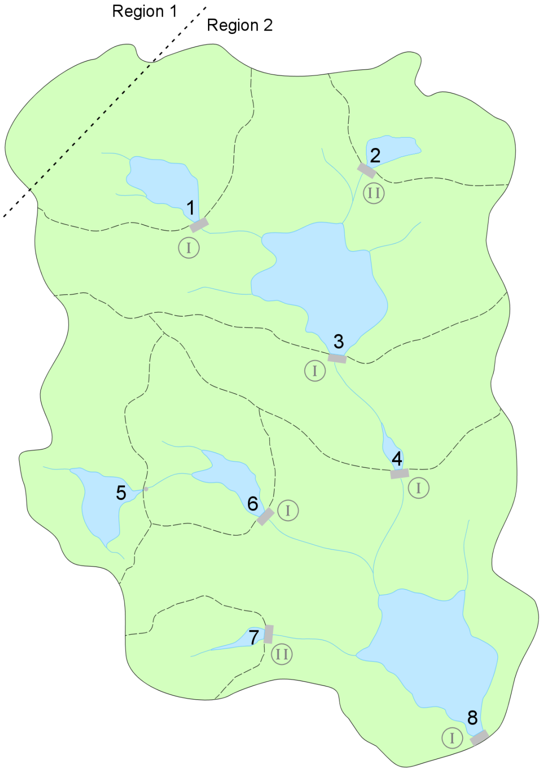

Figure 6 Schematic diagram of a fictitious system of dams and regulation reservoirs. (I and II indicate the application of calculation method I and calculation method II)

The design flood and calculation method for the dams included in the system have been determined on the basis of the consequences of a dam failure in accordance with the instructions in chapter 2. For each regulation reservoir, and for areas downstream of large lakes and regulation reservoirs, an assessment is made as to whether there is a need for local design flood calculation. Examples are given here of some of the cases where it may be necessary to perform local calculations. In practice, the calculation methodology can be applied to any point in watercourses.

Design flood calculations are performed for points 1–8 in the watercourse as follows:

Point 1 – Calculation method I:

The total design flood is calculated for subarea 1. In the calculation, the design precipitation sequence is weighted, and seasonal correction is introduced according to how much of the area lies in region 1 and region 2 respectively. The precipitation is area-corrected and altitude-corrected according to the mean altitude in subarea 1. In the case of dam 1, a regulation strategy is applied as described in section 4.7.

Inflow corresponding to annual probability 1:100 is calculated using calculation method II (frequency analysis) according to the instructions in chapter 5, which corresponds to the basic requirement concerning minimum discharge capacity at normal retention water level.

Point 2 – Calculation method II:

Inflow is calculated using calculation method II (frequency analysis) according to the instructions in chapter 5.

If observation data is available, time series consisting of each year's highest inflow to point 2 are used in the first instance.

Point 3 – Calculation method I:

The total design flood is calculated for subareas 1–3. The precipitation is area-corrected for the sum of the areas in areas 1–3 and altitude-corrected individually for each of subareas 1, 2 and 3. The discharge from areas 1 and 2 is then calculated by means of model simulation with this area and altitude correction. The regulation strategy according to section 4.7 is applied for all three dams 1, 2 and 3

Inflow flood corresponding to annual probability 1:100 is calculated using calculation method II (frequency analysis) according to the instructions in chapter 5, which corresponds to the basic requirement concerning minimum discharge capacity at normal retention water level.

Point 4 – Calculation method I:

The total design flood is calculated for subareas 1–4. The precipitation is area-corrected for the sum of the areas in areas 1–4 and altitude-corrected individually for areas 1, 2, 3 and 4. The regulation strategy for design in accordance with section 4.7 is applied for all dams 1–4.

Since the attenuation in the reservoir at point 3 is large and the local inflow downstream of the reservoir may be significant, a local calculation of the design flood for subarea 4 is also performed. Precipitation is then area-corrected and altitude-corrected according to the mean altitude in subarea 4, i.e. the design precipitation is assumed to fall only over subarea 4, while the inflow from other subareas is calculated with the aid of observed climate data. The regulation strategy according to section 4.7 is applied at dam 4. At the upstream dams 1, 2 and 3, the regulation strategy deemed to be reasonable in the current flood situation in these subareas is applied.

Inflow flood corresponding to annual probability 1:100 is calculated using calculation method II (frequency analysis) according to the instructions in chapter 5, which corresponds to the basic requirement concerning minimum discharge capacity at normal retention water level.

Point 5:

This is a natural lake that is regarded as a subarea so as to take into account its attenuating effect on the flood to the dam in point 6. The lake's discharge curve and storage at different water levels are determined or calculated. Uncertainties in the determination of the discharge capacity have a major impact on the calculation results downstream.

Point 6 – Calculation method I:

Design flood is calculated for areas 5 and 6. Precipitation is corrected for the sum of the areas in areas 5–6, and altitude correction is performed individually for each subarea.

If the attenuation of the lake is significant, a local calculation of the design flood for subarea 6 is performed. The design precipitation is then assumed to fall only over subarea 6, while the inflow from the natural lake is calculated with the aid of observed climate data.

Inflow flood corresponding to annual probability 1:100 is calculated using calculation method II (frequency analysis) according to the instructions in chapter 5, which corresponds to the basic requirement concerning minimum discharge capacity at normal retention water level.

Point 7 – Calculation method II:

Inflow is calculated using calculation method II (frequency analysis) according to the instructions in chapter 5.

If observation data is available, time series consisting of each year's highest inflow to point 7 are used in the first instance.

Point 8 – Calculation method I:

The total design flood is calculated for areas 1–8. The precipitation area is corrected for the sum of the areas in areas 1–8 and is corrected individually for the subarea in question. The regulation strategy for design in accordance with section 5.7 is applied for dams 1–4 and 6–8.

Because the local inflow downstream of the dams in points 3 and 6 may be significant, a local calculation of the design flood for subareas 4, 7 and 8 is also performed. The height correction is calculated individually for each of these areas. The design precipitation is assumed to fall only over subareas 4, 7 and 8, while the inflow from other subareas is calculated with the aid of observed climate data. The regulation strategy according to section 4.7 is applied for dams 4, 7 and 8. The regulation strategy deemed to be reasonable in the current flood situation in these subareas is applied at upstream dams 1–3 and 6.

A further check should then be carried out, where the local inflow from subareas 4, 5, 6, 7 and 8 is calculated in a corresponding manner. In this local calculation, the design precipitation is assumed to fall only over subareas 4–8, while the inflow from other subareas is calculated with the aid of observed climate data. The altitude correction is calculated individually for each of the subareas. The regulation strategy according to section 4.7 is applied for dams 6–8. The regulation strategy deemed to be reasonable in the current flood situation in these subareas is applied at upstream dams 1–4.

Inflow flood corresponding to annual probability 1:100 is calculated using calculation method II (frequency analysis) according to the instructions in chapter 5, which corresponds to the basic requirement concerning minimum discharge capacity at normal retention water level. If the watercourse is heavily affected by regulation, model-calculated inflow flood with standardized regulation (Hallberg et al., 2016a) can constitute data for frequency analysis in addition to or instead of observational data.

Appendix 4 Calculation method I – application examples

Calculation example, Håckren

In this example, a calculation is performed for the Håckren dam (Figure 7) located in the Storån river, a tributary of the Indalsälven river.

Figure 7. Ongoing construction work to provide the Håckren dam with a new surface spillway.(Photo: Vattenregleringsföretagen, 2006)

Facility data

The Håckren reservoir consists of a damming of lakes Aumen, Hottöjen, Gesten, Korsjön and Håckren along a 25 km section. The dam's catchment area is 1167 km^2, of which 8% is lake. The total reservoir volume is 700 Mm^3. The reservoir in Håckren is used both as an annual regulation reservoir and as short-term regulation for Sällsjö power station, which is adjacent to Håckren reservoir. Upstream of Håckren is Ottsjön, which is a natural lake.

Since no minimum discharge is prescribed, all water usually passes through the power station and a tunnel with an outlet in Lake Ockesjön. Discharge via surface spillway.

Input data and model

The HBV model is calibrated against local inflow (downstream of Lake Ottsjön) to the Håckren reservoir. Particular emphasis is placed on describing high flood peaks as accurately as possible. The catchment area consists of two subareas (Ottsjön and Håckren) in the model structure. Design flood calculation refers to the entire catchment area.

The model calculation uses meteorological land input data, as well as water level data for Håckren and discharge data at the outlet and inlet. The period 1999–2010 is used for calibration, and 1986–1999 and 2010–2016 are used as validation periods. Climate data for the period 1998–2017 is used to calculate the design flood.

Initial state and design snow cover

A simulation for snow calculation using the HBV model is performed for the period 1962–2017. The largest estimated snow cover during these 56 years falls on 2 May 1976, when the water content is 424 mm. Frequency analysis of the snow cover's annual maximum values using Gumbel distribution gives 407 mm as the size of the design snow cover. The latest date when the maximum snowfall occurs is 6 May (1981-05-06). The initial state for the design calculation is created for the following day, i.e. 7 May.

Regulation strategy

The regulation strategy for the calculation is applied as described in section 4.7.

Information is compiled on applicable minimum level and normal retention water levels, flow capacity of turbines, minimum discharge and discharge capacity at different water levels.

A regulation table is compiled for the model calculations, which means that the following strategy is applied for Håckren:

- From the beginning of the spring flood, a zero discharge is applied as there is no prescribed minimum discharge.
- When the reservoir level exceeds the 90% storage volume, the inflow is discharged through the power station, up to 50 m^3/s.
- When the reservoir level exceeds the 95% storage volume, the inflow is discharged through the power station, up to the maximum capacity (110 m^3/s).
- When the reservoir level exceeds the 98% storage volume, the surface spillway is used for spill discharge that increases linearly to the normal retention water level.
- The surface spillway is used for full spill discharge for water levels above the normal retention water level.

Design precipitation sequence

The entire catchment area is located in region 2. A precipitation sequence is applied according to Table 2. The design value for day 9 is 120 mm. The mean altitude of the catchment area is 820 m above sea level, which (according to Table 3) means that the sequence is altitude-corrected by +32.0%. The catchment area is 1167 km^2, which (according to Figure 4) means area correction to 98.3%. The highest daily precipitation after corrections is 155 mm.

Design flood calculation

The calculation is based on climate data for the period 1998–2017. The step length of 24 hours is used to offset the precipitation sequence. The assumed initial water level is +469.40, which means that the reservoir has been lowered (3.40 m above the minimum water level). The continuous change of seasonal correction according to Figure 5, as well as adjustment of temperature and precipitation according to section 4.9, is handled automatically in the hydrological model.

Results

The design occasion is an autumn occasion that occurs in August 2015 (Figure 8). The highest water level is obtained when the design precipitation sequence is superimposed over the days from 29 July to 11 August. This means that the greatest precipitation (155 mm) falls on 6 August.

The greatest inflow to the reservoir is 830 m^3/s and occurs on 7 August, while the greatest outflow occurs on 8 August and is 580 m^3/s. The water level in the reservoir will be at most +493.98 on 8 August, which means that the normal retention water level is exceeded by 1.08 m.

The calculations were checked at the modeler’s premises by someone other than the person who performed the calculations and the calculations were documented.

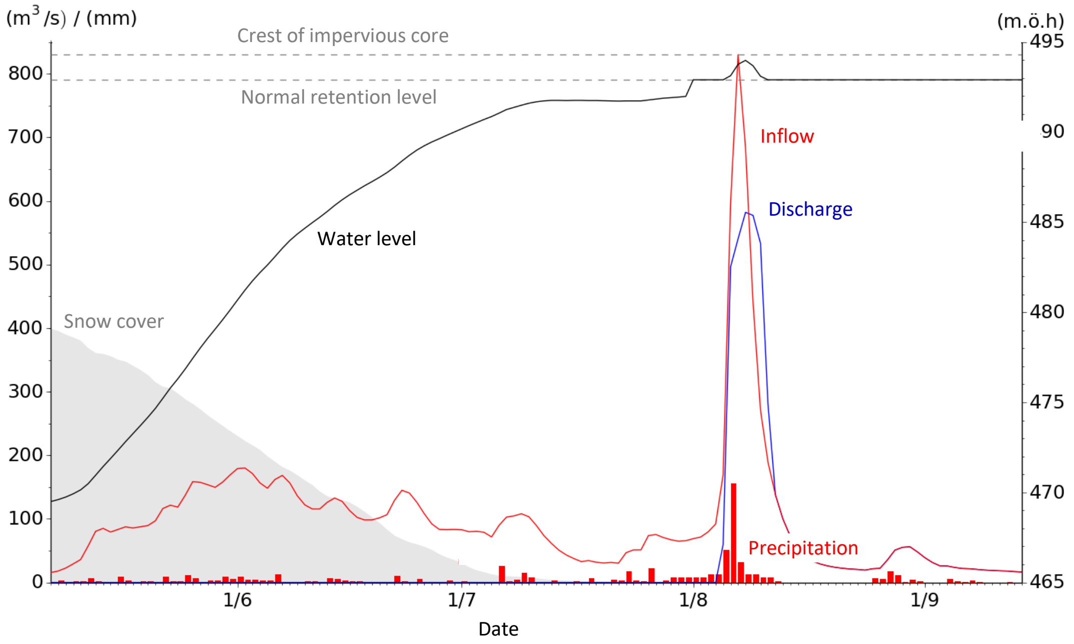

Figure 8. Design flood calculation for the Håckren dam.

Sensitivity analysis

In view of the integrated uncertainty in the calculations, the facility should have a margin to what the calculation result shows. There may be a need to carry out analyses of how large this margin should be. The appropriate analyses are dependent on the characteristics of the reservoir in question and/or the input data used in the calculation.

The quality of the input data affects the calibration of the model, which may be a source of error in the result. Inflow data during high flood periods may include sources of error due to the fact that a large part of the riverflow will consist of spill discharge with less accurate data quality. The scope of data, such as the length of time series for inflow, is also of importance. The model is primarily calibrated and validated for floods, which are unusual and occur to a greater extent if the time series are long. The documentation of the input data series and the calibration is thus important in order to draw conclusions on the reliability of the results (section 4.3).

The climate during the time period used in the calculations also affects the results. Another calculation period can be evaluated if there is any uncertainty as to whether the choice of calculation periods (for calculation of design snow cover and design flood) is representative.

The initial water level (residual reservoir storage level) may be of major significance for the calculation, which should be evaluated if there is any uncertainty as to which water level lowering can be assumed. One analysis is to show the sensitivity of the calculation to the residual reservoir storage, both at the specific facility and at upstream facilities, from a watercourse and river system perspective. A simple way of illustrating the impact of the residual reservoir on the results is to gradually set the initial storage volumes of e.g. 0%, 10%, 20%, etc. in the calculations in all upstream reservoirs and document the resulting design water levels. Figure 9 shows an analysis of Håckren's sensitivity to the residual reservoir storage.

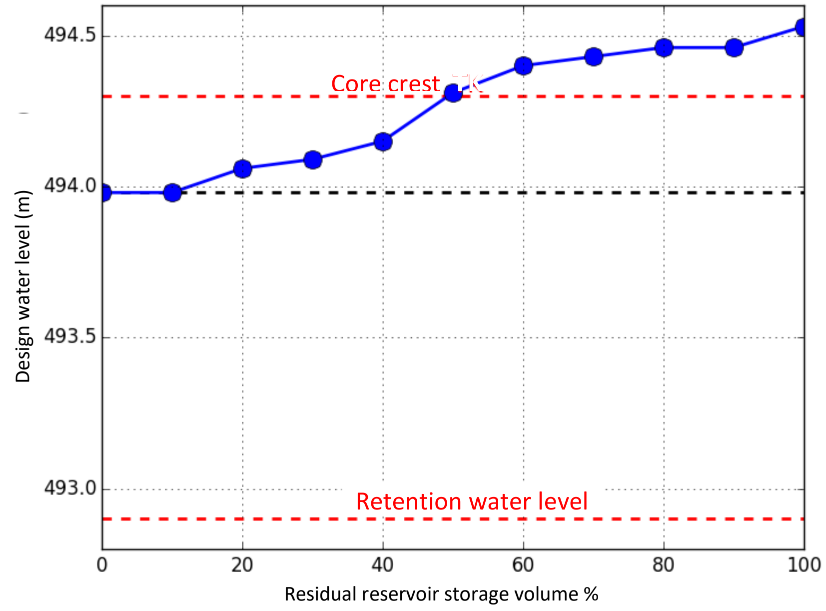

Figure 9. Sensitivity analysis for Håckren by gradually increasing the residual reservoir storage.

One way of analysing the margin to the facility's critical level is to evaluate whether the size and intensity of the inflow can increase without the design water level exceeding the upper edge of the impervious core or the crest of the dam, for example, and if so by how much. One simple way is to increase the design precipitation sequence in the calculation.

Table 5 shows a calculation for Håckren where the precipitation sequence has been adjusted upwards by changing the area factor. The results show that an increase of the area factor from 0.98 to 1.06 is required for the highest water level to reach the upper edge of the impervious core, which in this case entails an increase in precipitation volume, inflow volume and inflow maximum in the order of 10%.

Table 5. Sensitivity analysis for Håckren by increasing the design precipitation sequence.

Normal retention water level	**Crest of the dam core**	**Crest of the dam**	**Area factor**	**Precipitation sequence start date**	**Design occasion (date)**	**Precipitation sequence volume (mm)**	**Inflow volume (DE)**	**Inflow maximum (m^3/s)**	**Highest water level (m above sea level)**	**Increase in precipitation volume (%)**	**Increase in inflow maximum (%)**	**Increase in inflow volume (%)**
492.9	494.3	497.8	0.98	29/07/2015	08/08/2015	346	3691	830	493.98	-	-	-
			1.06	29/07/2015	08/08/2015	373	4014	914	494.30	8	10	9

Sensitivity analyses can be carried out along entire watercourses, which gives guidance on which facility has the smallest margin. This margin can in turn become the margin for all downstream facilities in the watercourse.

Sensitivity analysis with climate scenarios

There is no calculation with climate scenarios for Håckren, instead an example of a report of the results for Lake Kallsjön in the Indalsälven river is shown in Figure 10.

Since the area is situated in the vicinity and the design occasion for Lake Kallsjön also occurs during August, the example is also relevant for Håckren from several aspects. However, the design water level, which is facility-specific, is not. The climate scenarios show an increase in both volume and maximum intensity for the design precipitation sequence. The change in design water level is shown at the far right in Figure 10. The time for the design water levels and inflows for the different calculation periods is shown at the bottom of the figure.

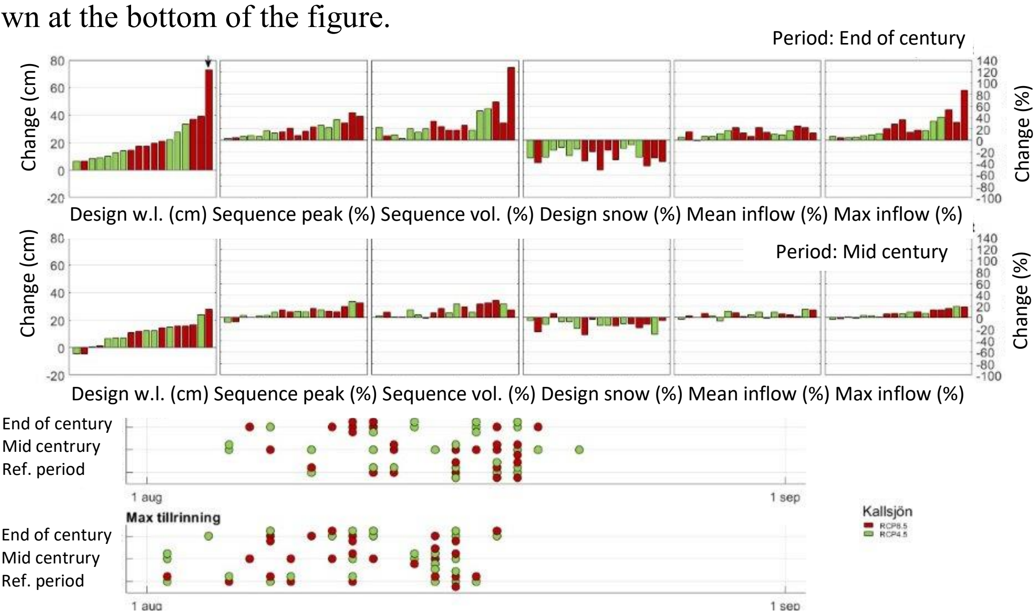

Figure 10. Percentage change for Lake Kallsjön in the Indalsälven river of sequence volume, sequence peak, design snow cover, mean inflow, maximum inflow at the design occasion, and change in design water level in cm according to 36 simulations (red=RCP 8.5, green=RCP4.5) that describe the end of the century (above) and the middle of the century (below) according to climate scenarios. The reference period against which the calculations are compared is 1971–1990. The time of the design water level for the three calculation periods is shown at the bottom.

Analysis of the calculation and its impact on dam safety work

In the example in question, the calculations show that the normal retention water level is exceeded by 1.08 m on the design occasion, but that there is still a margin to the crest of the impervious core. The design water level is 0.32 m lower than this and 3.82 m below the crest of the dam.

The conclusion is that the dam can withstand and convey safely a design flood according to calculation method I.

Documentation

Calculation by method I is documented both as a reporting document and as data in line with the RIDAS application guidance (Swedenergy, 2021).

The documentation includes:

1. Facility data

- *Coordinates*
  Coordinates of the calculation point
- *Characteristic inflow data*
  Characteristic inflow data at the calculation point is important for understanding the hydrology of the area and for comparison with the model results.
  LLT = Lowest measured daily mean inflow
  MLT = Mean of measured annual lowest daily mean inflows
  MT = Mean of measured daily mean inflows
  MHT = Mean of measured annual highest daily mean inflows
  HHT = Highest measured daily mean inflow
- *Statistical inflow data*
  Extreme inflow floods are calculated according to calculation method II, which can also be compared with historical events during the calibration and calculation period.
  HT100 = inflow flood with annual probability 1:100
  HT200 = inflow flood with annual probability 1:200
  HT500 = inflow flood with annual probability 1:500
- *Legal levels*
  The regulation procedure may include legal levels and flows.
  DG = normal retention water level
  SDG = summer normal retention water level
  SG = minimum water level
  SSG = summer minimum water level
  Qmin = minimum discharge
- *Technical dam levels*
  Technical dam levels that are important in the design work:
  TK = crest of impervious core (embankment dams)
  DK = crest of dam
- *Discharge capacity*
  The capacity of spillways.
- *Height system*
  The height system to which the calculations relate.
- *Justification for selecting input data*
  Different information may be available for the crest of the dam and impervious core depending on the part of the dam. Different information may also be

available regarding discharge capacities, results based on physical hydraulic models are normally preferable.

2. Regulation details

- *Minimum, mean and normal retention water levels for each day of the year*
  Diagram showing how the water level is regulated during the year.
- *Minimum, mean and maximum discharges for every day of the year*
  Diagram showing how the discharge is regulated during the year.
- *The lowest water level in the spring, for all regulated years in the series*
  The data for the annual lowest water level shows typical lowering of the reservoir before the beginning of the spring flood, which is a parameter in the model's initial state.
- *Description of the regulation strategy*
  A description in text of the model's regulation procedure that enables users of data to familiarize themselves with how the discharge from the reservoir is handled in the model.

  Some calculations may facilitate matters when setting-up the regulation strategy. These calculations should also be documented:

  - For reservoirs where the discharge is planned on the basis of the spring flood forecast, this can be done on the basis of the initial state for the design snow cover in question. The results of this calculation may help to develop reasonable regulation strategies within the framework of section 4.7 of the guidelines.
  - Analysis of how precautionary releases prior to the peak inflow and any active flood attenuation would affect the results for the facility in question and the facilities downstream.
- *Regulation strategy input data file*
  An input data file of the regulation strategy should be available.

3. Model details

- *Model, model version.*
  Specification of the model and model version in order to be able to reproduce model calculations.
- *Time steps*
  Time resolution of input data for the model.
- *Supplier*

4. Model calibration

- *Highest measured inflow during the calibration period*
  The higher and more well defined the inflow peaks used in the calibration and validation of the model, the better the conditions for the model to reproduce extreme floods effectively.
- *Calibration PM*

A document describing calibration at the calculation point where the quality of the calibration should be included. This should contain:
- calibration ranges included
- details of the length of the input data series
- information on the calibration period
- verification of calibration
- any comments regarding the quality of the inflow series and abnormal parameter values.

5. Design flood calculation (total and local calculation)

Both total and local calculations that have been performed should be documented. If any calculation alternative is omitted, the reason for this should be documented. This applies to the following information:

5.1 Area characteristics

- *Catchment area*
  The total (or local) catchment area is included in the calculation of the size of the precipitation sequence.
- *Mean altitude of catchment area*
  The mean altitude of the catchment area must be reported in cases where the value is included in the calculation of the size of the precipitation sequence.
- *Model structure*
  The calculation area's subareas and hydrological order must be presented.

5.2 Snow calculation

- *Calculation period*
  The choice of time period for calculating the snow cover's annual maximum water content may have an impact on the result.
- *Maximum water content and its date*
  The maximum model-calculated water content in the snow during the calculation period and the date on which it occurred.
- *Design snow cover (included in the initial state in the model calculations)*
  The water content in snow cover with annual probability of occurrence 1:30.
- *Last snow maximum date (included in the initial state in the model calculations)*
  The latest date during which the maximum water content occurred in all years of the calculation period.

5.3 Precipitation sequence

- *Region (included in calculation of the precipitation sequence size)*
  The regions in which the calculation area lies and their interrelationships as a percentage.
- *Altitude correction*
  The altitude-dependent factor multiplied by the precipitation sequence.

- *Area correction*
  The factor that is dependent on the area of the calculation area.

5.4 Design data

- *Calculation period*
  The time period used in the model to superimpose flood-creating factors and identify the highest calculated water level.

5.5 Results of design occasion

The following information should be reported from both spring and autumn occasions:

- *Sequence start*
  First day of precipitation sequence
- *Maximum precipitation in the sequence*
  The highest value in the precipitation sequence (day 9)
- *Maximum inflow*
  The highest inflow during the flood peak
- *Maximum outflow*
  The highest outflow during the flood peak
- *Highest water level*
  The highest water level during the inflow peak
- *Hydrograph (should be saved digitally in e.g. Excel)*
  Visualization of the flood peak, ideally with all of the following parameters in the same figure: inflow, outflow, water level, snow cover water content, precipitation and temperature (see Figure 8 in Appendix 4).

6. Sensitivity analysis

Analyses of uncertainties in calculation assumptions and calculation results, as well as analysis supported by climate scenarios. The analyses that should be carried out may depend on the characteristics of the actual reservoir and the quality of the input data used in the calculation, for example.

6.1 Sensitivity analysis for changed climate

A report on the sensitivity of the calculations to a changed climate documents in which emission scenarios, global climate models, regional climate models (or equivalent if other than dynamic downscaling has been used) and scaling methodology have been used to produce forcing data for the hydrological model. Normally, the analysis of the sensitivity of the facility to a changed climate is preceded by design flood calculations according to the present guidelines, and the model is already documented in this case. If this is not the case, documentation should be prepared for the hydrological model used. Methodology for calculating the change in the precipitation sequence must also be documented and shown.

The outcome of the calculations should be documented so that variation between scenarios can be seen; as in Elforsk report 14:27 (Hallberg, et al., 2014), for instance.

6.2 Analysis of sensitivity in input data and calculation conditions

Sensitivity analyses performed and the results of these are documented. The methodology for the sensitivity analyses must also be presented.

Depending on the characteristics of the reservoir, there may be a need to analyze the sensitivity of the facility to variations in calculation conditions such as regulation strategy and the reservoir water level at the start of calculation by varying the conditions. Another, or a longer, period can be used if there are uncertainties as to whether the time period used for the calculation is representative.

Sometimes it may also be beneficial to conduct an analysis of the facility's margin for coping with a greater inflow than what the result of the design calculation shows, which can then be evaluated (see Appendix 4).

7. Modeler

Quality assurance includes specifying who performed calculations of the design flood and compiled the documentation, and who performed the review of the calculations.

8. Administration/archiving

To be able to reproduce and check calculation results, it should be clear how and where the original documents and calculations are administered and archived.

Appendix 5 Calculation method II – application examples

Calculation example Bålforsen

In this example, a frequency analysis is carried out to calculate the size of the inflow that corresponds to the annual probability 1:100 of the power station dam at Bålforsen in the Umeälven river. The facility is situated about 90 km downstream of Lake Storuman and consists of a concrete dam and power station that were commissioned in 1958. The reservoir is used for short-term regulation on a daily basis. Discharge up to a maximum of 315 m^3/s usually goes through the power station. If a higher discharge is required, water is discharged via the spillway, which has a capacity to discharge a total of 2220 m^3/s at the normal retention water level.

Input data

Different types of data are available for the facility. Observed inflow in 1976–2015 and data from hydrological model simulations with standardized regulation in 1976–2015. Base data (high flood discharge) has been quality-controlled and deemed usable for the analysis.

The facility's storage volume is small, which is why discharge floods largely corresponds to the inflow, but the overall effect of regulating the storage reservoir upstream is considerable. Most of the reservoirs on the Umeälven river were built in the 1950s and 1960s. Additional regulations after the 1970s are deemed to have only had a minor impact downstream, which is why 1976–2015 is used for frequency analysis. The data is shown in *Table 6*.

Table 6. Data for frequency analysis at Bålforsen.

Year	Max. observed inflow flood (m^3/s)	Max. simulated inflow flood (m^3/s)	Year	Max. observed inflow flood (m^3/s)	Max. simulated inflow flood (m^3/s)
1976	313	343	1996	311	352
1977	301	430	1997	545	802
1978	305	381	1998	877	858
1979	304	436	1999	317	409
1980	301	323	2000	887	835
1981	901	695	2001	786	802
1982	303	301	2002	375	369
1983	394	648	2003	277	302
1984	395	415	2004	841	1183
1985	803	714	2005	326	459
1986	407	441	2006	312	302
1987	922	848	2007	312	458
1988	310	551	2008	355	428
1989	467	416	2009	304	545
1990	719	524	2010	347	457
1991	334	462	2011	670	602
1992	413	440	2012	546	622
1993	1210	1096	2013	308	301
1994	303	412	2014	308	253
1995	553	554	2015	610	642

Frequency analysis

The calculations are based on the annual maximum inflow flood, a total of 40 years of data. The Log-normal, Gumbel and GEV distribution functions are adapted to the respective data series. The parameters in the distribution functions are calculated using the maximum-likelihood method (MLE), and for Gumbel distribution using the method of moments (MOM) as well. Statistical goodness of fit tests Kolmogorov-Smirnov, Cramér von Mises, Kuiper and Anderson-Darling are calculated and provide numerical values for how well the distribution fits with the data. These fit tests can be used both as a test of whether the distribution is suitable for data and as a comparison measure between distributions.

Figure 11 shows the frequency distributions adapted to observation data (inflow flood), while Figure 12 shows the frequency distributions adapted to inflow flood simulated using a hydrological model and standardized regulation. Statistical goodness of fit test are presented in Table 7 and Table 8. Inflow floods corresponding to annual probability 1:100, 1:200 and 1:500 are presented in Table 9 and Table 10.

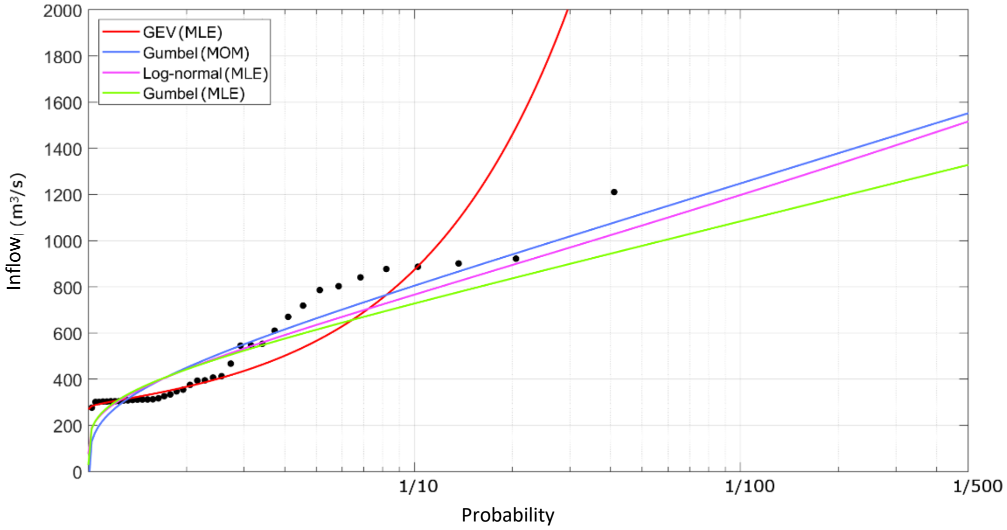

Figure 11. Frequency analysis of observation data (inflow flood) for Bålforsen in 1976–2015.

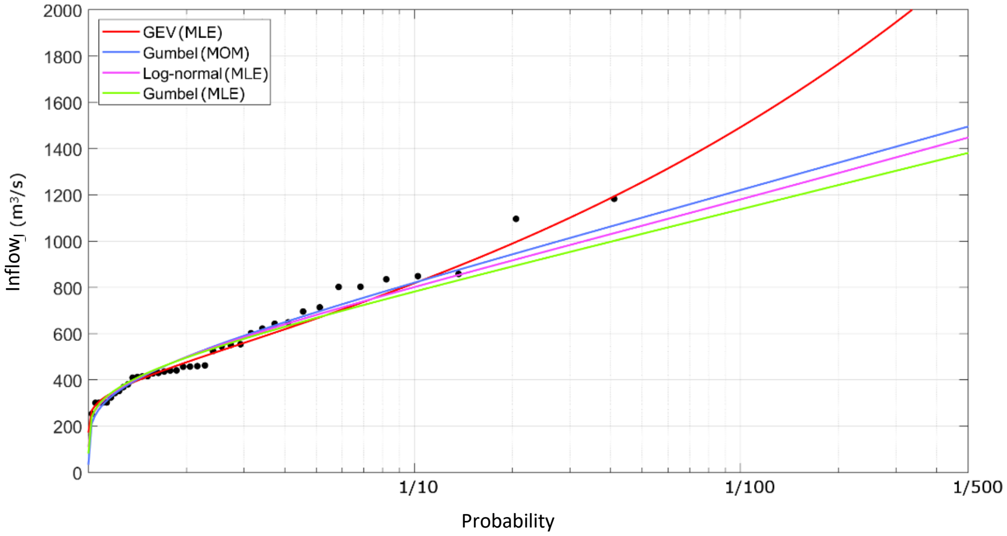

Figure 12. Frequency analysis of inflow flood to Bålforsen simulated by means of a hydrological model and standardized regulation in 1976–2015.

Table 7. Adaptation measure for frequency analysis of observation data (inflow flood) for Bålforsen in 1976–2015.

Goodness of fit test	**Frequency distribution**			
	Gumbel (MLE)	Gumbel (MOM)	GEV (MLE)	Log-normal (MLE)
Kolmogorov-Smirnov	0.98	0.96	0.84	0.96
Kuiper	0.39	0.39	0.29	0.37
Cramér-von Mises	0.54	0.45	0.20	0.48
Anderson-Darling	0.05	0.02	0.02	0.03

Table 8. Adaptation measures for frequency analysis of inflow flood to Bålforsen simulated by means of a hydrological model and standardized regulation in 1976–2015.

Goodness of fit test	**Frequency distribution**			
	Gumbel (MLE)	Gumbel (MOM)	GEV (MLE)	Log-normal (MLE)
Kolmogorov-Smirnov	0.85	0.84	0.53	0.85
Kuiper	0.29	0.28	0.19	0.28
Cramér-von Mises	0.10	0.09	0.05	0.09
Anderson-Darling	0.01	0.01	0.00	0.01

Table 9. Extreme inflow floods (m^3/s) calculated from observation data (inflow) for Bålforsen in 1976–2015 with different frequency distributions. Values in brackets indicate 95% confidence intervals.

Annual probability of inflow*	**Frequency distribution**			
	Gumbel (MLE)	Gumbel (MOM)	GEV (MLE)	Log-normal (MLE)
1:100	1085 *(710–1460)*	1245 *(785–1720)*	5750 *(820–56930)*	1195 *(750–1700)*
1:200	1190 *(725–1660)*	1380 *(801–1965)*	10770 *(865–192095)*	1330 *(760–1985)*
1:500	1325 *(735–1930)*	1550 *(812–2300)*	25015 *(895–1010025)*	1515 *(770–2405)*

*Probability of the flood occurring or being exceeded in a single year

Table 10. Extreme inflow floods (m^3/s) calculated from inflow flood simulated by means of a hydrological model and standardized regulation in 1976–2015 with different frequency distributions. Values in brackets indicate 95% confidence intervals.

Annual probability of inflow*	**Frequency distribution**			
	Gumbel (MLE)	Gumbel (MOM)	GEV (MLE)	Log-normal (MLE)
1:100	1135 *(765–1515)*	1220 *(800–1645)*	1490 *(795–2700)*	1180 *(785–1600)*
1:200	1240 *(780–1715)*	1340 (815–1870)	1765 *(815–3645)*	1295 *(800–1830)*
1:500	1380 *(790–1980)*	1495 *(825–2170)*	2195 *(825–5440)*	1445 *(805–2160)*

**Probability of the inflow occurring or being exceeded in a single year

Results

Statistical goodness of fit tests show that all distribution functions have poor adaptation to observation data, while the adaptation to model-simulated inflow flood is better, which shows that data simulated with standardized regulation is preferable. The choice of simulated data can also be justified by a clearer link to underlying hydrological processes, in contrast to observational data where the maximum annual volume consists of full production discharge. Of the investigated frequency distributions, GEV shows the best goodness of fit, while the others show slightly poorer fit, but are equivalent. The large confidence intervals indicate that the calculation results have great uncertainty.

Extrapolation of the frequency curves against the result of calculation method I (2154 m^3/s) is shown graphically in Figure 11 and Figure 12. In this case, GEV is shown to give unreasonable results. Other frequency distributions are deemed reasonable, but Gumbel distribution adapted to the method of moments links up more effectively to the highest annual maximums.

In this example, simulations with a hydrological model have been deemed to be the most suitable basis for the facility in question. The example is from an analysis of the entire river, where it turned out that Gumbel distribution adapted with the method of moments provides a coherent picture for adjacent facilities as well, and is thereby selected as the applicable method. The result for calculation method II for Bålforsen is that the inflow with a probability of 1:100 of occurring or being exceeded is calculated at 1220 m^3/s, the inflow with a probability of 1:200 is calculated at 1340 m^3/s, and the inflow with a probability of 1:500 is calculated at 1495 m^3/s.

At the normal retention water level, the facility is able to cope with the inflow with an annual probability of 1:100 occurrence or being exceeded, even within the known uncertainty (confidence interval) of the calculation.

Documentation

Calculation method II is documented both as a reporting document and as data in line with the RIDAS application guidance (Swedenergy, 2021).

The documentation includes:

1. General information

- *Coordinates*
  Coordinates of the calculation point
- *Catchment area*
  Area of the total and local catchment area
- *Facility data*

Any information about legal levels, technical dam levels, discharge information, changes in the facility and regulation, etc. which are of importance for the implementation of the frequency analysis

- *Changes in regulation conditions*
  Description of when upstream regulation reservoirs were commissioned and whether they may have been changed, so that this can be compared with the period for which the frequency analysis was carried out
- *Input data quality*
  Quality of the input data is documented.

2. Frequency analysis

- *Inflow series*
  All data series (annual maximum) used and the time when they have occurred
- *Selection criterion for data in the analysis*
  Reasons for selection/calculation of data (annual maximum) included in the analysis
- *Frequency distribution function(s)*
  Description of the frequency distribution function(s), with the relevant parameter estimation method, used in the frequency analysis and reasons for which one has been selected as applicable
- *Frequency distribution diagram*
  All frequency analyses used is ideally presented in one and the same diagram
- *Confidence interval*
  The known uncertainty of the calculation is ideally presented in the table
- *Results of frequency analysis*
  The results for all frequency analyses used are ideally presented in tabular form.
  HT100 = inflow with annual probability 1:100
  HT200 = inflow with annual probability 1:200
  HT500 = inflow with annual probability 1:500

3. Sensitivity analysis

The calculation may contain more steps and uncertainties that may need to be elucidated. One such aspect is the choice of distribution function, where results from several distribution functions should be reported. The sensitivity of the calculation to uncertain input data can be investigated if there is uncertainty, e.g. for annual maximum values used or if the available data periods differ between the data points.

If an analysis of sensitivity to climate change has been performed, which emission scenarios, global climate models, regional climate models (or equivalent if other than dynamic downscaling has been used) and scaling methodology have been used to produce forcing data for the hydrological model must be documented. The hydrological model used and how it is set up and calibrated should also be documented.

4. Modeler

Quality assurance includes specifying who performed the calculations and compiled the documentation, and who performed the review of the calculations.

5. Administration/archiving

To be able to reproduce and check calculation results, it should be clear how and where the original documents and calculations are administered and archived.