Swedish Guidelines for Design Flood Determination for Dams

New edition 2007

Svenska Kraftnät

SVENSK energi

SveMin

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Cover picture: Stadsforsen hydropower plant at river Indalsälven. Photo: Bengt Johansson, Vattenfall

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Preface

This document is a new edition of the Swedish guidelines for design flood determination for dams, published in 1990 by The Swedish Committee for Design Flood Determination. Additions and changes after 1990 have been included and the language has been simplified and elucidated. This new edition consequently replaces the guidelines in the final report of The Swedish Committee for Design Flood Determination and the subsequently made additions 1-3.

The guidelines are primarily directed to dam owners and consultants who carry out design flood calculations. The term guidelines implies that these instructions are not legally binding rules or regulations.

The implications of the original guidelines with additions are mainly unchanged in the new edition. The methodology of the guidelines have not been revised, considering expected future climatic change, but the application of the guidelines in a changing climate is considered in the new edition.

The responsibility for the new edition is shared between Svenska Kraftnät, Swedenergy and SveMin. The new Committee for Design Flood Guidelines for Dams (KFR) has been in charge of the revision and this task has been carried out by Marie Gardelin (SMHI, Swedish Meteorological and Hydrological Institute) on behalf of KFR. KFR consisted of the following members: Sten Bergström (SMHI), Claes-Olof Brandesten (Vattenfall), Tina Fridolf (Svenska Kraftnät until March, 2007), Maria Bartsch (Svenska Kraftnät from August, 2007), Lars-Åke Lindahl (SveMin), Olle Mill (Svenska Kraftnät; Chairman of KFR), Urban Norstedt (Vattenfall), Gunnar Sjödin (Water Regulating Enterprises) and Gun Åhrling-Rundström (Swedenergy).

Contents

Summary

The Swedish design flood guidelines were originally published by The Swedish Committee for Design Flood Determination (Flödeskommittén) in 1990. The guidelines were an important upgrade to Swedish dam safety criteria regarding extreme floods. The following report constitutes a new edition of the guidelines, which henceforth replaces those from 1990 and the subsequently issued additions. The guidelines are primarily directed to dam owners and consultants who carry out design flood calculations.

Design flood determination is based on a classification into two categories depending on the potential consequences of a dam failure during flood conditions. Flood Design Category I should be applied to dams for which failure could cause loss of life or personal injury, considerable damage to infrastructure, property or the environment, or other large economic damage. Flood Design Category II should be applied to dams for which failure could only cause damage to infrastructure, property or the environment.

Design flood determination in Flood Design Category I should be based on hydrological modelling techniques that describe the effects of extreme precipitation under particularly unfavourable hydrological conditions. In the calculations, extreme precipitation is assumed to coincide with heavy snowmelt and wet soils. Critical flows and water levels are simulated over a period of at least ten years, by systematic replacement of observed precipitation in different areas, using a moving 14-day design precipitation sequence.

The different flood generating factors, each within limits of what has been observed, are combined to give the most critical total effect on the river system. With all unfavourable conditions assumed to occur at the same time, the result is very extreme floods. Dams in Flood Design Category I should be able to withstand and pass a flood determined by this method without serious damage to the structure. The return period of floods cannot be estimated using this approach. However, comparisons with frequency analysis indicate that such floods, on average, have return periods exceeding 10 000 years. An additional stipulation is that dams in Flood Design Category I should also be able to pass a flood with a return period of at minimum 100 years at normal retention water level.

Dams in Flood Design Category II should be able to pass a flood with a return period of at minimum 100 years at normal retention water level. Frequency analysis is applied for this determination. Dams in Flood Design Category II should also be adapted to a flood determined by cost-benefit analysis. Under this criterion, selection of a flood higher than the 100-year flood is stipulated if the additional cost for this does not greatly exceed the benefit.

The intent of the original guidelines is basically unchanged here and the methods have not been revised to take into account expected future climate changes. The new edition does, however, address how to apply the guidelines to a changing climate. Included are also recommendations for documentation and examples of design flood calculations.

1 Background

In 1985 the Swedish hydropower industry and SMHI, the Swedish Metheorological and Hydrological Institute, decided to establish the Committee for Design Flood Determination, assigned the task of elaborating guidelines for the determination of design floods at hydropower and regulating dams. The Committee, with representatives of the hydropower industry and SMHI, investigated the design flood determination methods previously used in Sweden and abroad, and initiated studies of runoff data and extreme areal precipitation observed in Sweden, among other things. Also a new method for design flood determination for dams of the highest consequence category was developed.

The results were stated in the final report of the Committee for Design Flood Determination (Flödeskommittén, 1990). The hydro power industry accepted to adhere to the guidelines and to accept an active responsibility when applying them. Originally the guidelines were designed for hydropower dams, but they have also been applied to safety dykes and mine dams, as well as when determining floods in inundation mapping.

The implementation of the guidelines for design flood determination has been going on since 1990 and implies an important upgrading of Swedish dam safety in terms of ability to handle extreme floods. In 1991 a special consultation forum, the so-called Flood Conference (Flödeskonferensen) was established between the principals of the guidelines. The task of the Conference is to monitor the relevance of the guidelines and the continuing implementation of them. Over the years, the guidelines have been completed with three additions. A compilation of design flood calculations carried out until 2003 in accordance with the guidelines for design flood determination comprises close to 700 locations in the country (Brandesten et al., 2006).

After the guidelines were originally published in the final report of the Committee for Design Flood Determination, the issue of possible influence on extreme floods by a future climatic change has received increasing attention. A number of studies into possible changes in extreme floods in Sweden have been carried out (Andréasson et al., 2007; Andréasson et al., 2004; Bergström et al., 2001; Gardelin et al., 2002). Their results indicate that global warming would probably produce reduced spring floods, but at the same time an increased risk of precipitation floods in summer, autumn and winter. This change would be a result of winters becoming shorter and less stable, and the expectation that the precipitation increases, above all in western and northern Sweden.

Initiated by the Flood Conference and in cooperation with the mining industry, a new Committee for Design Flood Guidelines (KFR) was established in 2002. The Committe was assigned the task of making a review of the guidelines for great lakes with limited discharge capacities and of mining dams and other dams with a limited catchment area. Also the Committee was assigned the task of discussing an overall strategy for the handling of the climate issue. The work of the Committee was described in a report published in 2005 (KFR, 2005).

Svenska Kraftnät (in its role as national authority for dam safety), Swedenergy (in its role as hydro power industry organization) and SveMin (the Swedish Association of Mines, Mineral and Metal Producers) have jointly appointed KFR to be in charge of the production of a new edition of the Swedish guidelines for design flood determination for dams. The intention of this new edition is to give the guidelines a new, easier to follow formulation and to include the additions and changes after 1990. The new edition replaces the guidelines in the final report of the Committee for Design Flood Determination and additions made since. The new, shorter edition means that it was not possible to include all background material. Readers are kindly adviced to consult the final report of the Committee for Design Flood Determination and the 2005 KFR report for further studies and more information about the background of the guidelines.

2 Changes in comparison with the 1990 guidelines

A review of the terms in the guidelines resulted in the term *Risk Category,* used in the final report of the Committee for Design Flood Determination, being replaced by the term *Flood Design Category*. The new edition also differs from the previous one regarding validity, since the guidelines for new dams and for existing ones are not treated separately. Furthermore the application of the guidelines on mining industry dams has been elucidated in the new edition. Also a section on documentation, competence and quality assessment has been added.

The conclusions of the 2005 KFR report have been included in the new edition and the application of the guidelines in view of the future climate is also considered. The methodology of the guidelines has however not been revised and the contents of the original guidelines, with additions, are mainly unchanged, with the following exceptions:

- The validity of the guidelines when designing according to Flood Design Category I is enhanced and now includes catchment areas down to a size of 1 sq. km. (section 5).
- In the new edition it is stated that design flood calculation in Flood Design Category I is based on climate data representative of conditions in the area, whilst in the final report of the Committee for Design Flood Determination it was stated that data available for a recent period had been used (section 5.2).
- The geographical regions where the guidelines are valid have been enlarged, to comprise the entire runoff area of Sweden, i.e. also parts of Norway and Finland (section 5.10).
- Reservation is also made for the applicability of the guidelines to Lake Vänern and possible other cases similar to Vänern (section 5.15).
- No difference is made between existing and new dams regarding adaptation of dams in Flood Design Category II to a new, higher flood than the 100 years flood (section 6), determined according to a cost/benefit analysis.
- The guidelines regarding temporary dams/retention dams in the final report of the Committee for Design Flood Determination have not been included in the new edition, since these guidelines have been considered inadequately elaborated.

3 Application

These guidelines are intended for the determination of design floods at hydropower industry and mining industry dams. Design flood determination for the post-closure phase for certain mining waste deposits has not been included, because of the long time perspective in these cases. The guidelines should be applied to dams being planned, as well as when making control calculations on existing dams. In the calculation methodology, the river is seen as a system, which makes coordination and cooperation between dam owners necessary. The calculation methodology has also been used when designing flood protection dikes for municipalities and infrastructure, and when mapping inundation risks.

The determination of design floods is based on statistical methods or on simulations, using hydrological models. Both methods contain elements of uncertainty which should be accounted for when the results are evaluated. The selection of a time period providing the basis for the calculations is most important and should be taken into special consideration. Other uncertainty factors are discussed more thoroughly in the description of the calculation methodology (sections 5.1 and 6.1).

In the light of the uncertainties created by climate change, among other things, it is advisable that the calculation assumptions are revised regularly. Comparisons should continuously be made between actual flood occurrences and calculated design floods. The sensitivity of the system to climatic change should be analyzed, using climate scenarios. New conditions could produce a need for a revision of the design calculations. Uncertainties about the climate in the future should however not stop the implementation of measures to increase dam safety. Furthermore, flexibility and margins should be created where appropriate, in view of these uncertainties.

4 Classification of dams in flood design categories

When determining design floods for dams, a classification according to flood design categories is applied. This classification is made according to which consequences a dam failure could produce as a result of large floods (Table 1). The guidelines are not applicable to dams that in case of a dam failure would not cause damage to anyone, except the dam owner.

Table 1. Flood Design Categories when determining design floods.

Flood Design Category *)	**Dam failure consequences** (beside consequences of the flood as such, apart from a dam failure)	**Discharge requirements**
I	• Not negligible probability of risk of loss of human life or injury to person or • Noteworthy probability of serious damage to important traffic routes, dams or comparable constructions, or important environmental values or • Considerable probability of major economic damage	• The dam should, without serious damage to the dam, be able to withstand and pass a design flood determined according to the instructions of section 5 **). • The dam should at normal retention water level be able to pass an inflow flood with a return period of at least 100 years.
II	• Not negligible probability of damage to traffic routes, dams or comparable constructions, environmental values or property owned by someone other than the dam owner in cases not stated in Design Flood Category I.	• The dam should at normal retention water level be able to pass an inflow flood with a return period of at least 100 years. • The dam should furthermore be adapted to a flood determined through a cost/benefit analysis.

*) *The term "flood design category" replaces the term "risk class" used in the 1990 final report of the Committee for Design Flood Determination.*

**) *The flood return period cannot be stated using this method. Comparisons with frequency analysis indicate that floods calculated this way have return periods of more than 10 000 years, at an average.*

The classification is based on the concept of incremental consequences, i.e. the additional damage following a dam failure. The damage in this context is the increase of damage to the surroundings caused by the dam failure, in addition to the damage that the flood would have caused, had the dam not failed.

The assessment of which flood design category a certain dam should belong to, could only be made in the individual case. Firstly, the risk of loss of human life and injury to people should be evaluated. Secondly the consequences of a dam failure for downstream dams, public constructions and private property should be evaluated. Important traffic routes, road and railway bridges and other societal constructions of great importance to the society, such as water and sewage utilities, and energy supply installations, are among these public constructions. The environment is also a public interest and could be damaged following a dam failure. In this context damage to the natural environment, housing areas, with sanitary conditions included, and historic and cultural values should be considered. Consequences labelled major economic damage could e.g. relate to the risks of inundation affecting major industrial plants.

The term *considerable probability* means that there is a high degree of probability that a certain damage would occur, according to a competent analyst. The term *not negligible probability* means that it is not certain at all that the damage would occur, but that this possibility should be included and consequently also taken into consideration. The term *noteworthy probability* is intended to cover the space between considerable and not negligible probability, corresponding to what is colloquially known as rather high, down to rather small probability.

When for example the risks of loss of human life or serious injury to people is assessed, the probability is considered *high* if there are houses in the risk area where people live all the year. The probability is considered *noteworthy* if there are some holiday cottages in the area and *not negligible* if there is a public camping ground. If the risk area is all woodland where normally no-one goes, the probability that e.g. someone picking mushrooms or an orienteer getting injured could be considered so small as to be *negligible*.

The term *return period* of an event means that at an average this event occurs or is surpassed once during this period. This implies that the probability of e.g. a 100 year flood is 1 in 100 every single year. The accumulated probability increases, since one is exposed to the risk during several years. The probability that a 100 year flood would occur during a 100 year period is 63 %. Table 2 shows the relations between return period, time of exposure and probability.

Table 2. Connection between return period, time of exposure and probability, percent.

Return period (yrs)	Probability during 50 years (%)	Probability during 100 years (%)
100	39	63
1000	5	9.5
10 000	0.5	1

5 Design flood calculation for dams in Flood Design Category I

Dams classified in Flood Design Category I should withstand and be able to pass a design flood calculated according to the guidelines of this section without serious damage to the dam. If nothing else is prescribed, it should also be able to pass an inflow flood with a return period of 100 years at normal retention water level. This requirement has been added primarily to diminish the risk of high water levels that could cause inundation damages along the banks of the reservoir. This requirement may be conceded at existing dams to the extent that, in view of the safety of the dam and the risk of damage to the dam, it is considered enough that this flood could be passed at a water level surpassing the normal retention level. To determine the 100 year inflow flood, frequency analysis according to section 6 is applied.

The described method is applicable to catchment areas down to the size of 1 sq. km. For the smallest catchment areas there is however reason to study the effects of using a time resolution higher than 24 hours in the calculations.

5.1 Methodology

The method to determine the design flood for dams in Flood Design Category I is based on hydrological model simulations describing the consequences of extreme precipitation under particularly unfavourable conditions. The generation of the design flood is simulated using established hydrological modelling techniques. 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 calculations will simulate the critical flows and water levels as the actually observed precipitation during various periods is exchanged for a design precipitation sequence. Figure 1 is summarily describing the execution of the design calculations.

This design method implies that a number of flood generating factors, each within limits of what has been observed, are combined so as to produce the most critical total effect on the river system. The size of the design precipitation sequence has been established through the analysis of observed extreme area precipitation in different parts of Sweden. In the 1990 final report of the Committee for Design Flood Determination the 24-hour precipitation was mainly based on observations during 1881-1988 (Vedin and Eriksson, 1988). Observations after 1990 have by and large confirmed the reasonableness of these values, although a certain increased frequency of extreme rains has been observed (Alexandersson, 2005).

The precipitation is only one of several factors determining the size of the design flood. The desired safety margin is attained when observed precipitation is combined with other factors affecting the size of the flood. The total effect when all unfavourable conditions occur at the same time is very extreme floods. The return periods of a flood can, however, not be established using this method but comparisons with frequency analysis indicate that floods calculated this way have return periods of more than 10 000 years, at an average (the Committee for Design Flood Determination, 1990).

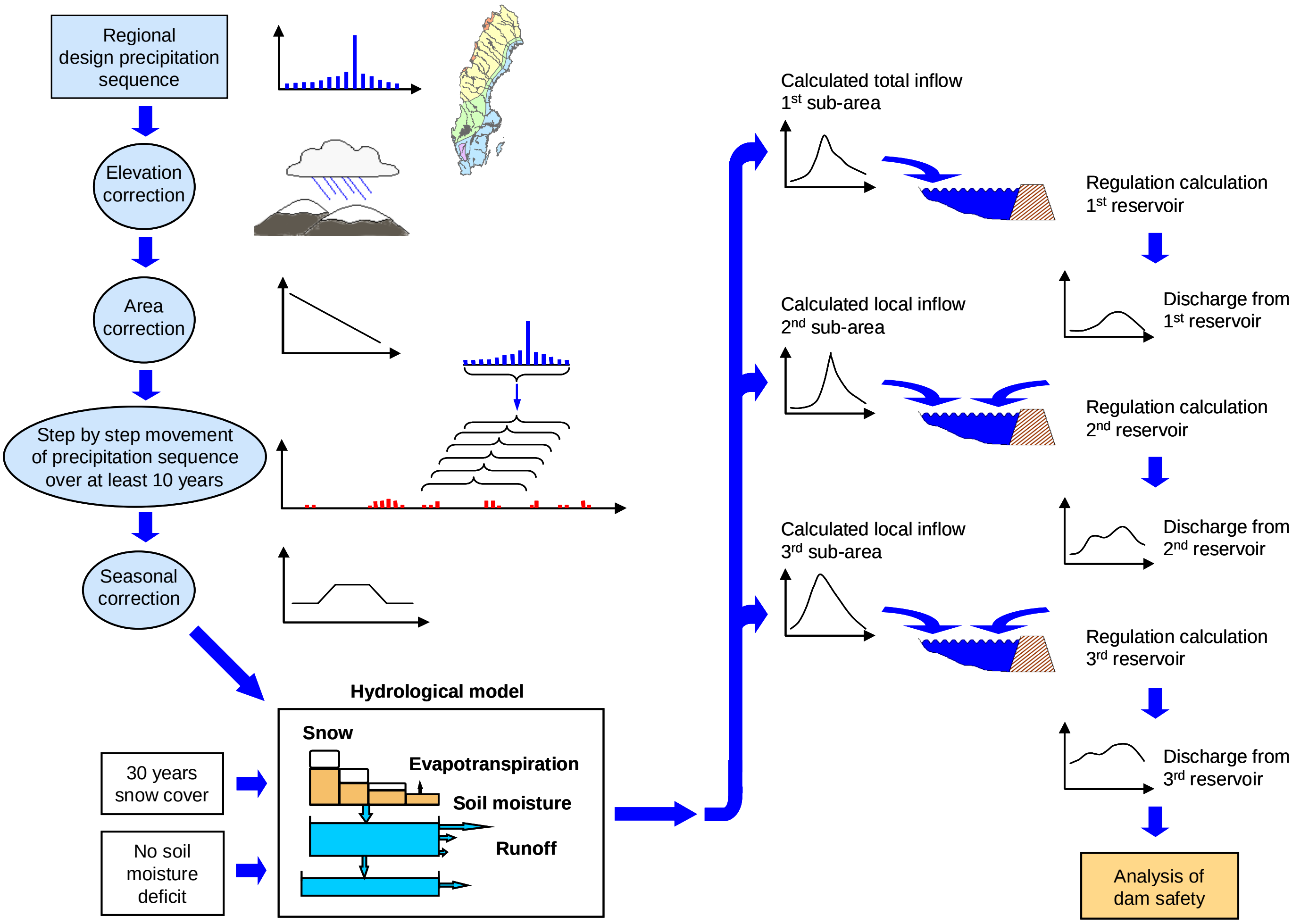


Figure 1. *A principal drawing of the calculation of the design flood for a dam in Flood Design Category I.*

In many countries, where hydrological model simulations are utilized in a similar way in design calculations, the terms PMP (Possible Maximum Precipitation) and PMF (Probable Maximum Flood) are used. PMP refers to the theoretically maximum precipitation physically possible on a certain area during a given period of time and at a certain time of the year. The definition of PMF is different in different countries, but often refers to the most critical reasonable combination of meteorological and hydrological conditions in a given region. PMF is established through various sorts of hydrological model calculations with PMP being used as in-data. A principle difference between these methods and the design of dams of Flood Design Category I according to the Committee for Design Flood Determination guidelines is that the PMP value is established theoretically and surpasses the levels that have occurred when observing precipitation, whilst the size of the design precipitation sequence in Flood Design Category I has been established using observations of extreme area precipitation.

Following the publication of the Committee for Design Flood Determination guidelines in 1990, the methodology for flood calculation has been presented in international journals (Norstedt et al., 1992; Bergström et al., 1992; Lindström and Harlin, 1992). The methodology has also been discussed at a number of scientific conferences. Furthermore, a number of extreme floods have occurred in regulated rivers, e.g. in 1995 and in 2000. The overall evaluation is that the guidelines are describing the generation of extreme floods in a realistic way. What happened around Lake Vänern during the autumn and winter of 2000/2001 however showed that the guidelines cannot be categorically applied to Vänern, due to the special conditions of this system (KFR, 2005).

There are several sources of uncertainty that should be taken into account when the results of the design calculations are evaluated and used. The results are affected by which meteorological and hydrological data are used in the modelling calculations, as well as by the choice of hydrological model. The ability of the model to describe the generation of high floods is the basis of the design calculation and depends on several factors such as model structure, calibration method and choice of time period for the calibration. Further development of the hydrological models, as well as development of new methods to establish in-data, consequently affect the results of the design. The description of river regulations and the discharge from natural lakes would also have an influence. Furthermore, the choice of calculation period when simulating extreme floods, as well as when establishing the design snow cover, have also shown to influence the calculation results to a great extent.

5.2 Data basis

For the hydrological model calculations, forming the foundation when calculating floods of Flood Design Category I, records of meteorological as well as hydrological observations are needed. The quality of the calculation results is dependant on the reliability of this data basis. Normally the calibration of the hydrological model requires about 10 years of data. The data records should comprise high spring floods as well as heavy rains. For the model calculation of the snow cover it is advisable to use an extended period of time, since a maximum mass of snow with a return period of 30 years is utilized in the design calculation.

The design calculation, when the most critical flood is identified, is based on climate data representative of the climatic conditions in the area and comprising a period of at least 10 years.

5.3 Model structure

A catchment area is divided into sub-areas if it contains more than one regulation reservoir, if parts of the catchment area contains large lakes or if the area is in other respects so heterogeneous that it should not be regarded as an entity. This division means that water level changes and discharge are individually calculated for each sub-area. A sub-area could e.g. be major non-regulated lakes or river stretches that could possibly function as retention reservoirs in a flood situation. Sub-areas could also be established at locations where there is access to records of discharge, to make it possible to calibrate the model at these locations.

5.4 Model calibration

The hydrological model is calibrated against available series of inflow data. In this, special emphasis should be put on the model reflecting high floods as correctly as possible. Furthermore, when modelling a whole river system great emphasis should be put on describing the function of the whole river during extreme conditions in a realistic way.

5.5 Snow cover calculation

A simulation is made using the hydrological model to determine annual maximum values for the model-calculated snow cover during the time period available. Frequency analysis is made to determine the maximum water content of the snow at a 30 years return period. The latest date on which the snow cover culminated during one of the analyzed years is determined. In the design calculation it is assumed that the snow cover has the same relative distribution between high altitude zones and sub-areas as shown by the model calculation when the maximum snow cover occurred.

5.6 Initial conditions

The calculation of the design flood starts when spring begins after a snowy winter which is assumed to have been preceded by an autumn with much precipitation. When starting the calculation, the following conditions consequently are assumed:

- No soil moisture deficit in the entire catchment area.
- Existing reservoirs have been drawn down to levels considered reasonable when a large spring flood is expected.
- Flows in the river system are at normal values, awaiting the spring flood.

The starting date of each year's calculation is fixed to the day after the latest date at which the snow cover culminated during any of the years analyzed. The maximum water content of the snow with a 30 years return period is assumed at the starting date.

5.7 Regulation strategy

The following regulation strategy is to be applied at every important regulation reservoir in the system:

- When the reservoir is starting to fill up, it is presumed that a minimum discharge is carried out at a prescribed rate and that the production discharge is on-going at a rate considered reasonable when a strong spring flood is forecasted. If it is assumed that pre-determined releases will be prescribed, this must also be taken into consideration.

- When it is assumed that the maximum precipitation will occur (from day 9 in the precipitation sequence and onwards), it is presumed that the production discharge stops and that discharge could be made only through the spillways (maximum discharge according to the discharge curve).

- After the reservoirs of the system have reached their individual normal retention water levels, which presumably would be August 1st at the latest, the reservoirs are assumed not to be lowered below the normal retention water level until the critical flood period of the region is over.

When applied to mining dams, the regulation strategy may have to be adapted to the special conditions at these dams.

5.8 Discharge capacity

When calculating the discharge capacity of a dam, only the documented capacity of spillways being readily available should be included in the calculation. Possible discharge options through hydropower turbines must not be included from the day of the culmination of the design precipitation sequence and onwards. Furthermore possible head losses in the headrace and tailrace channels, as well as other obstacles to the runoff of the water, affecting the total discharge capacity of the dam, must be taken into consideration.

Information about the discharge capacity of dams and reservoir level/storage curves are produced and added to the model. If the retention and discharge capacity of any of the upstream dams is below what is required to pass the design flood at this dam, then it may initially be presumed that this dam has been reconstructed so as to pass the flood without damage to the dam. Then the safety of this upstream dam should also be analyzed. The results of this analysis could lead to a reconsideration of the design calculation for the downstream dam.

5.9 Flood attenuation

In the design calculation for an existing dam, realistic possibilities may be considered of attenuating the flood at this dam or at another upstream dam, the owners of which have agreed to cooperate in flood attenuation.

Passive flood attenuation implies that the system has a discharge capacity automatically limiting and attenuating the flood. This is applicable to most natural lakes and many regulation reservoirs. For a design calculation to count in the effect of passive attenuation it is required that there is a reservoir volume available when the design flood occurs at maximum discharge. This implies that no active measures are carried out to attenuate the flood. In this case the flood will be automatically attenuated by the discharge limitations of the system.

Active flood attenuation implies that the regulation reservoir is actively utilized to diminish the downstream flows by limiting the spillway flow to less than its maximum capacity at a certain water level. As in the case of passive flood attenuation a reservoir volume, ready to be utilized when the design flood occurs, is required. Applying active flood attenuation is a complicated procedure requiring careful analysis of the function of the entire water system for critical flood situations. Also a discharge strategy is required, as robust as to be applicable and deliver intended results even in cases when communications are down and information about downstream reservoirs and installations is failing. Active flood attenuation should be applied in a careful manner and only when large reservoir volumes with certainty are at hand to produce the attenuating effect in a critical situation. This method also requires a decisions-process well rehearsed that will function in a critical situation.

5.10 Precipitation sequence

The build-up and course of the design flood is simulated using hydrological modelling technique with the 14-day design precipitation sequence replacing observed precipitation. The design precipitation sequence (Table 3 and Figure 3) is specific for different regions in Sweden according to Figure 2.

If the catchment area is situated on high altitudes, then the fact that precipitation normally increases with the height above the sea must be considered. The increase is dependant on geographic location and so different corrections are used for different catchment areas in Sweden (according to Table 4).

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

Area correction factor = 1,78 − 0,26 · log (catchment area in sq. km.) *Eq. 1*

Furthermore the precipitation sequence should be corrected according to the time of the year when the precipitation presumably occurs. The seasonal correction should be made continuously during the step by step movement of the precipitation sequence, described in section 5.11. The 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 the peak value of the sequence and the other values are however corrected according to different curves. The seasonal correction is illustrated in Figure 5 and is made as follows:

Region 1:
The values in the precipitation sequence according to Table 3, peak values included, are assumed to be valid at 100 % from July 16th to March 31st. From then on, the values are diminished linearly down to 50 % on April 30th and then a linear increase up to 100 % on July 16th is assumed.

Region 2 - 4:
The values in the precipitation sequence according to Table 3, their peak values included, are assumed to be valid at 100 % from July16th to August 15th. From then on, the values are diminished linearly down to 50 % on November 16th. From November 16th up to April 30th the values are assumed to stay at 50 % and then a linear increase up to 100 % on July 16th is assumed.

Region 5:
The peak values of the precipitation sequence (day 9) is corrected according to the seasonal variations in regions 2 - 4, i.e. the peak value according to Table 3 is assumed to be valid at 100 % from July16th to August 15th. From then on the value is diminished linearly down to 50 % on November 16th. From November 16th until April 30th the value is assumed to stay at 50 % and then a linear increase up to 100 % on July16th is assumed. The other values in the precipitation sequence are assumed to be valid at 100 % from July 16th until August 15th. From then on the values are diminished linearly down to 65 % on November 16th. From November 16th until April 30th the values are assumed to stay at 65 % and then a linear increase up to 100 % on July 16th is assumed.

5.11 Design floods and water levels

Extreme floods are simulated during the period of time chosen, using the hydrological model and the assumed regulation strategy. Doing this, the actual measured 14-day precipitation is replaced with the design precipitation sequence (Table 3). With a corresponding alteration of the seasonal correction, this sequence is then moved in time and then a new calculation is made. Moving the precipitation sequence and the corresponding flood calculation is made in steps of 24 hours for all years included in the design calculation. The most critical development at a dam simulated this way will provide the design.

To avoid unrealistic combinations of heavy precipitation and high temperature during the spring flood, the measured temperature is lowered by 3°C during days 9-14 in the precipitation sequence in the period January 1st - July 31st. To avoid unrealistically heavy 14-day precipitations, caused by the design sequence ending close to observed heavy precipitation, it is permitted to reduce observed precipitation values close to the sequence, so that a running 14-day value does not exceed the sum total of the design sequence.

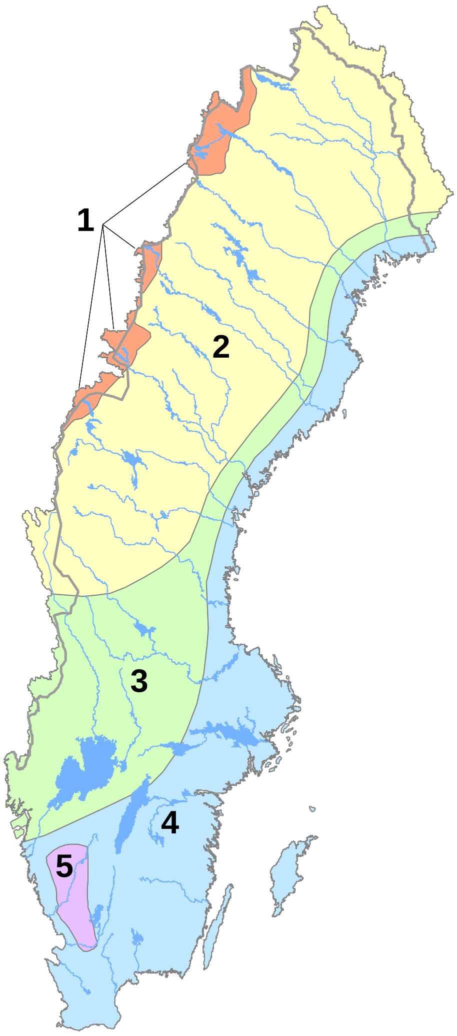


Figure 2. Regional division when choosing design precipitation sequence and seasonal correction.

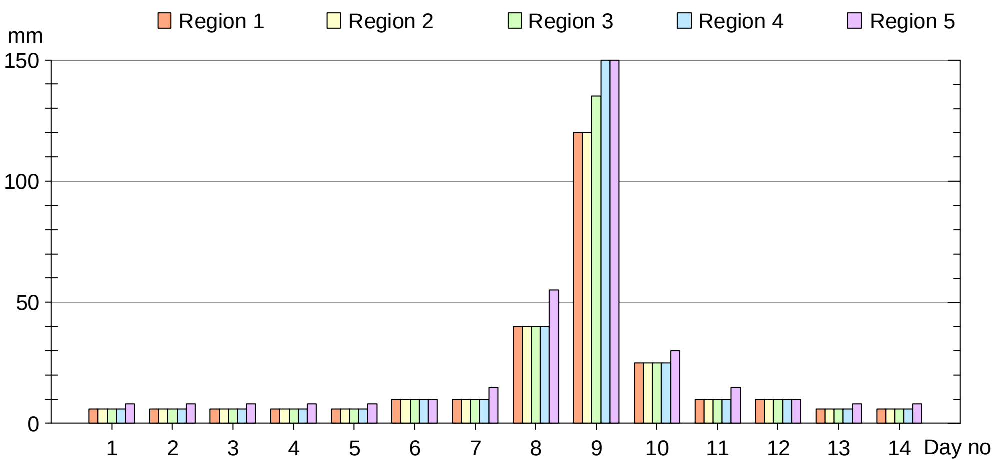


Figure 3. Design precipitation sequences for different regions in Sweden. The diagram shows areal precipitation on 1000 km² as mm/24h.

Table 3. Design precipitation sequences for different regions in Sweden. The table shows areal precipitation on 1000 km² as mm/24h. (Regional division is shown in Figure 2. See also 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

Table 4. Elevation correction of the precipitation sequences and the reference level that the correction is made from.

Catchment area	Elevation correction (increase of precipitation sequence per 100 m above reference level)	Reference level (m. above sea level)
River Torneälv to river Indalsälven	10 %	500
Rivers Ljungan and Ljusnan	10 %	600
River Dalälven	5 %	600
River Klarälven	5 %	700

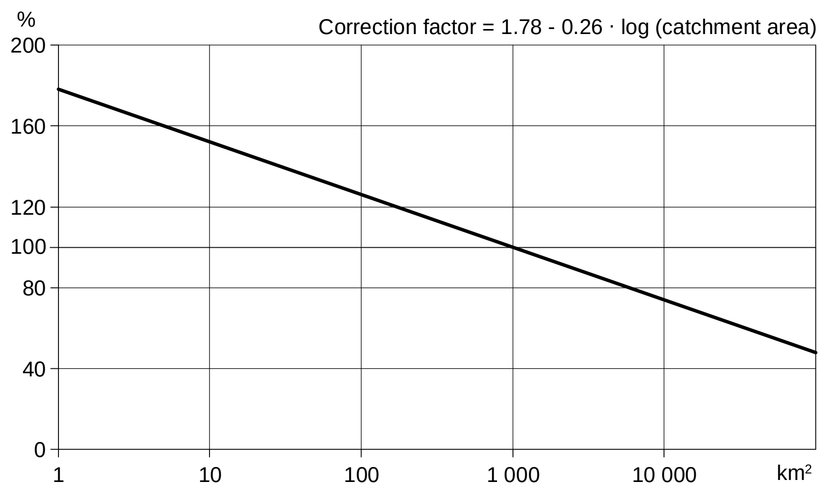


Figure 4. Area correction factor for the design precipitation sequences.

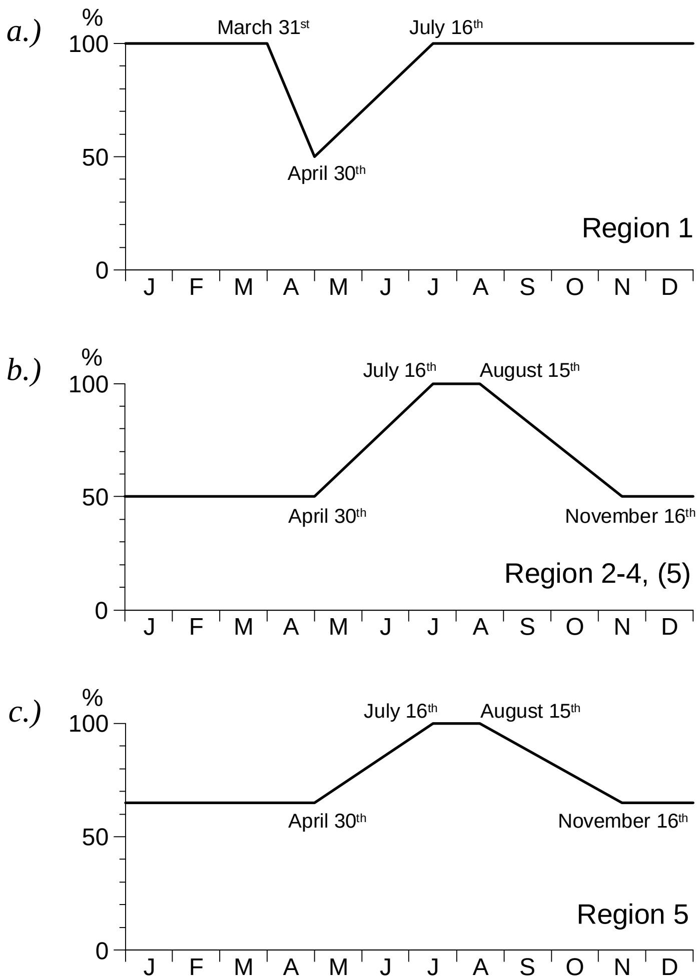


Figure 5. Seasonal correction of the design precipitation sequence.
a.) Correction in region 1 of all values in the sequence.
b.) Correction in regions 2 - 4 of all values in the sequence and in region 5 of the sequence´s peak value (day 9).
c.) Correction in region 5 of the sequence´s values, except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

5.12 Local design

Besides design flood calculations for the entire catchment area, design flood calculations are also carried out for the local catchment areas of each regulation reservoir. In local design, the height and area correction of the precipitation sequence, as well as the design snow cover applicable to the local area, is applied, whilst the added flow from the other sub-areas are calculated using records on observed climate for the design period chosen.

If there are large natural lakes in the river system, attenuating the flow from part of the catchment area, a local design calculation is made also for the area downstream from the lakes.

5.13 Wind influence

Waves and wind set-up due to the influence of wind should be considered, assuming a wind from the most unfavourable direction at 25 m/s for dams above the tree limit and at 20 m/s for other dams.

5.14 Analysis

When the design calculations have been carried out according to this, the ability of the dams to retain and discharge the design floods is analyzed. This implies an overall analysis including facts about waves and wind set-up, and the water level development in relation to the heights of the impervious cores and dam crests. When measures are required to comply with the design flood, the calculation procedure is repeated. The model is updated with the new assumptions, as e.g. a change of discharge strategy or an increased discharge capacity, and then a new design calculation is carried out.

5.15 Large lakes with limited discharge capacity

In most cases, these guidelines may be applied also to large lakes with a limited discharge capacity. A deeper analysis is however required for lake Vänern and possibly also other lakes which like Vänern have special runoff conditions, including an upper limit to permitted discharge.

6 Design flood determination for dams in Flood Design Category II

Dams designed according to Flood Design Category II should be able to pass an incoming flood with a return period of a minimum 100 years at normal retention water level. At existing dams this requirement may be conceded to the extent that, considering the safety of the dam and the risk of damage to the dam, it is considered adequate that this flood can be passed at a water level surpassing the normal retention water level.

The calculation of the 100 year flood is based on time series of inflow data at the dam. Extrapolation to the required return period of the flood is made with frequency analysis.

Furthermore, dams classified in Flood Design Category II should also be adapted to a flood determined through cost-benefit analysis. In this, a flood greater than the 100 year flood should preferably be chosen if this added cost does not considerably surpass the benefit, i.e. the estimated value of avoiding the risk of a dam failure because of the design flood being surpassed.

At existing reservoirs where a possible failure in any dam of the system would imply only limited damages, those exceptions may be made from a strict application of the flood design guidelines that are considered reasonable and proper when comparing reconstruction costs and disturbances on one hand, and the risk of damages on the other.

6.1 Methodology

The 100 year return period flood is calculated through frequency analysis. This implies that a time series compiled by the maximum inflow of each year is adapted to a frequency distribution function, producing the 100 year return period flood. A number of distribution functions may be chosen. Under Swedish conditions one of the distribution functions Gumbel, Gamma or Lognormal, all with two parameters, are usually preferred. The calculations are based on the inflow to the reservoir and not the discharge. This means avoiding the effect of a perhaps non-existing attenuation to the calculations.

There are several sources of uncertainty in the frequency analysis. The choice of time period affects the results, as does the choice of frequency distribution. It may be difficult to apply frequency analysis to streams that are severely affected by regulation and especially so if the size of the regulation has been gradually changed during the period when data have been gathered. It is advisable to try more than one type of distribution function and to carry out the calculation based on various time periods. The frequency analysis could be complemented with a calculation of confidence limits to get a picture of the uncertainty in the calculation.

6.2 Data basis

Time series of inflow to the reservoir are required in the frequency analysis for the design calculation in Flood Design Category II. The series should preferably be longer than 50 years, but if such data are not available one would have to carry out the analysis on a shorter period of time. A shorter series would increase the uncertainty and also the requirements that the period chosen should be representative of the climate in the region. If there are no local observations, then the calculations can be carried out using information on the records of discharge in some other part of the water course or in some adjacent water course.

6.3 Discharge capacity

When calculating the discharge capacity of a dam, only the documented capacity of spillways being readily available should be included in the calculation. Possible discharge options through hydropower turbines must not be included. Furthermore possible head losses in the headrace and tailrace channels, as well as other obstacles to the runoff of the water, affecting the total discharge capacity of the dam, has to be taken into consideration.

6.4 Wind influence

Waves and wind set-up due to the influence of wind should be considered, assuming a wind from the most unfavourable direction at 25 m/s for dams above the tree limit and at 20 m/s for other dams.

7 Implementation

7.1 Documentation

Each design flood calculation should be documented in a way enabling the reconstruction of the calculation when needed. The documentation should comprise information about:

- calculation method
- hydrological data base, i.e. time period and station information for hydrological in-data
- results on calculated design floods and water levels

From model calculations for dams in Flood Design Category I documentation should furthermore be produced on:

- climate data base - time period and geographical distribution (station data or area data)
- time period for model calibration, snow calculation and design calculation
- model version
- model structure - division of sub-areas
- local designs - investigation about the need for them and calculations carried out
- regulation strategies, including information about active or passive attenuation
- parameter values and calibration criteria
- initial conditions
- snow cover - maximum water content with a 30 years return period
- date when design precipitation sequence was started
- date for design floods and water levels

In section 8 examples are given of suitable documentation of design calculations.

7.2 Competence

The calculation of design floods is a complicated task requiring hydrological competence and relevant knowledge within water regulation and dam safety. The calculations should be carried out by persons having experience of hydrological modelling and a good knowledge of regulation of hydropower dams and of mining.

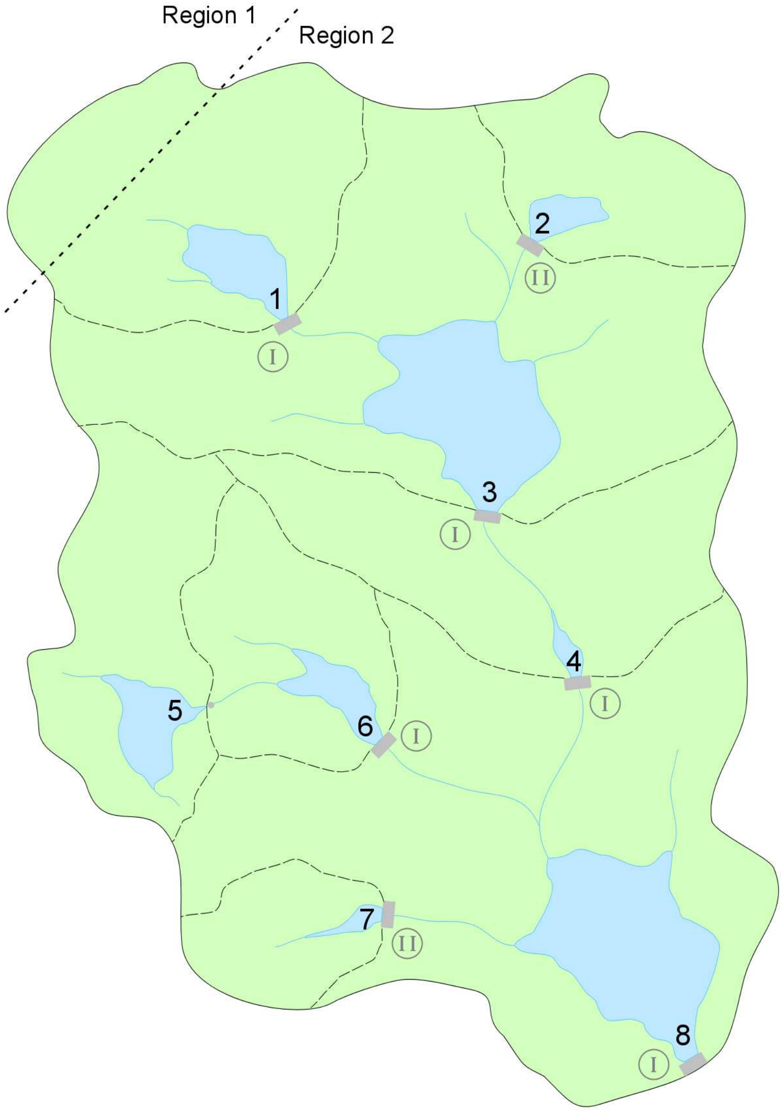
7.3 Quality assessment

The calculation of design floods is an extensive procedure with many sub-operations. Therefore routines should be established to secure the quality of the results. The quality assessment should imply that the calculations are by routine checked by some other person than the one carrying out the calculations.

8 Calculation examples

8.1 Principles of a river system calculation

In this section the principles of design flood calculations are described for various parts of a river system with a number of dams and regulation reservoirs, as well as natural lakes and streams. The structure of the river system is outlined in Figure 6.



Figur 6. Outline of a fictitious system of dams and regulation reservoirs. (I and II are showing Flood Design Category.)

The Flood Design Category of the dams in the system is determined by the consequences of a dam failure, according to the guidelines in section 4 (see Table 1). A special cost-benefit analysis is made for dams of Flood Design Category II, not shown in this example. An assessment is made of each regulation reservoir and for areas downstream of large lakes an assessment is made of the need for a local flood design calculation. Examples of some cases when a local flood design calculation would be needed are shown here.

Design flood calculations are carried out at different points in the stream according to the following:

Point 1 - Flood Design Category I:

Total design flood calculation is made for sub-area 1. The design precipitation sequence is weighted in the calculation and the seasonal correction is added according to the size of the part of the sub-area being in region 1 or in region 2. The precipitation is area-corrected and height corrected according to the average height in sub-area 1. At dam 1 a regulation strategy for flood design according to section 5.7 is applied.

The incoming 100 year flood is calculated using frequency analysis according to the instructions of section 6.

Point 2 - Flood Design Category II:

As starting point of the design flood calculation the floods with a 100 years return period area calculated using frequency analysis according to the instructions in section 6. If data are available, time series of the maximum inflow each year is primarily used for point 2.

Point 3 - Flood Design Category I:

Total design flood calculation is made for sub-areas 1-3. The precipitation is area corrected for the sum total of the areas in sub-areas 1-3 and is individually height corrected at each of the sub-areas 1, 2 and 3. The discharge from sub-areas 1 and 2 is calculated using model simulation with this area and height correction. At all three dams 1, 2 and 3 a regulation strategy for the flood design according to section 5.7 is applied.

The incoming 100 year flood is calculated using frequency analysis according to the instructions in section 6.

Point 4 - Flood Design Category I:

Total design flood calculation is made for sub-areas 1-4. The precipitation is area corrected for the sum total of the areas in sub-areas 1-4 and is individually height corrected at each of the sub-areas 1, 2, 3 and 4. At all dams 1-4 a regulation strategy for the flood design according to section 5.7 is applied.

Since the attenuation in the reservoir at point 3 is considerable and the local inflow downstream of the reservoir may be considerable, a local design flood calculation is also made for sub-area 4. The precipitation is area corrected and height corrected according to the average height in sub-area 4, i.e. the design precipitation is assumed to fall only on sub-area 4, and the inflow from the other sub-areas is calculated using observed climate data for the flood design period. At dam 4 a regulation strategy for flood design according to section 5.7 is applied. At the upstream dams 1, 2 and 3 a regulation strategy regarded reasonable in actual flood situations in these sub-areas is applied.

The incoming 100 year flood is calculated using frequency analysis according to the instructions in section 6.

Point 5:

This is a natural lake which is regarded as a sub-area since its attenuating effect on the inflow to the dam at point 6 should be taken into consideration. The runoff curve and retention at various water levels of the lake is determined or calculated. Uncertainties when determining its discharge capacity has a major influence on the downstream design flood results.

Point 6 - Flood Design Category I:

Total design flood calculation is made for sub-areas 5 and 6. The precipitation is area corrected for the sum total of the areas of sub-areas 5-6 and height correction is made individually for each sub-area.

If the attenuation in the lake is considerable, a local design flood calculation is made for sub-area 6. The design precipitation is assumed to fall on sub-area 6 only, whilst the inflow from the natural lake is calculated using observed climate data for the flood design period.

The incoming 100 year flood is calculated using frequency analysis according to the instructions in section 6.

Point 7 - Flood Design Category II:

As the starting point for the design flood calculation, floods with a 100 years return period are calculated using frequency analysis according to section 6. If data are available, time series of the maximum inflow each year is primarily used for point 7.

Point 8 - Flood Design Category I:

Total design flood calculation is made for sub-areas 1-8. The precipitation is area corrected for the sum total of the areas of sub-areas 1-8 and height correction is made individually for each sub-area. At the dams 1-4 and 6-8 a regulation strategy for flood design according to section 5.7 is applied.

Since the local inflow downstream of the dams of point 3 and 6 may be considerable, a local design flood calculation is made for sub-areas 4, 7 and 8. The height correction is calculated individually for each of these sub-areas. The design precipitation is assumed to fall on sub-areas 4, 7 and 8 only, and the inflow from the other sub-areas is calculated using observed climate data for the design flood period. At dams 4, 7 and 8 a regulation strategy for design flood calculation according to section 5.7 is applied. At the upstream dams 1-3 and 6 a regulation strategy considered reasonable in the actual flood situation in these sub-areas is applied.

After this another check should be made, calculating the local inflow from sub-areas 4, 5, 6, 7 and 8 in a corresponding manner. In this local design flood calculation the design precipitation is assumed to fall only on sub-areas 4-8, whilst the inflow from the other sub-areas is calculated using observed climate data for the design period. The elevation correction is calculated individually for each sub-area. At dams 6-8 a regulation strategy for flood design according to section 5.7 is applied. At the upstream dams 1-4 a regulation strategy considered reasonable in the actual flood situation in these sub-areas is applied.

The incoming 100 year flood is calculated using frequency analysis according to the instructions in section 6.

8.2 Design flood calculation at a dam in Flood design Category I

In this example, a design flood calculation is made at the Håckren dam in Storån, a tributary stream to river Indalsälven. The reservoir comprises lakes Aumen, Hottöjen, Gesten, Korsjön and Håckren along a 25 km stretch of the river. The catchment area of the dam is 1167 km^2, 8 % of which is lakes. The total reservoir volume is 700 Mm^3. The Håckren dam is utilized both as a seasonal storage reservoir and as a short-time regulation facility for the Sällsjö hydropower station in the vicinity of the Håckren dam. Upstream of Håckren is lake Ottsjön, a natural lake.

No minimum discharge being prescribed, all water is usually passing the hydropower station and a tunnel with its outlet in lake Ockesjön. At very high floods water can be discharged through a tower spillway to the original stretch of the river and on to lake Sällsjön.

8.2.1 In-data och model

The HBV model has been calibrated on the inflow to the Håckren reservoir. Special emphasis has been put on describing high flood peaks as correctly as possible. The catchment area comprises two sub-areas (lakes Ottsjön and Håckren) in the model structure. A total flood design calculation is made for the entire catchment area.

In the model calculation meteorological in-data from 3 precipitation stations and 2 temperature stations are used, and water level data for Håckren and water flow information from inflow and discharge. Climate data for the 1973-1991 period have been used in the calculation. The 1982-1991 period has been used for calibration and the 1973-1981 period has been used as verification period.

8.2.2 Design snow cover and starting date

A simulation for the snow calculation using the HBV model is made for the period 1973-1991. The largest calculated snow cover during these 19 years occurs May 2nd, 1976, when the water content is 419 mm. Frequency analysis of the yearly maximum values of the snow cover using Gumbel distribution results in a snow cover with a 30 years return period being 414 mm. The latest date when snow maximum occurs is May 6th (1981). The starting date for the flood design calculation is set to the next day, May 7th.

8.2.3 Regleringsstrategi

A regulating strategy for the design flood calculation according to instructions in section 5.7 is applied.

Information is compiled about existing minimum water levels, normal retention levels, extended discharges, minimum discharge and discharge capacity at various water levels.

For the model calculations a regulation table is compiled, implying that the following strategy is used applied at Håckren:

- Before the start of the spring flood (until April 30th) an even lowering of the water level down to the minimum level is carried out (+ 466.00).
- When the spring flood has started, zero discharge is applied since no minimum discharge has been prescribed.
- At a water level between + 491.50 (1.40 m below normal retention level) and + 492.40, the inflow is discharged up to the extended discharge of 110 m^3/s.
- At water levels above + 492.40 maximum discharge is made through the tower spillway.
- On October 1st the discharge period starts and a rectilinear lowering is applied until April 30th next year.

8.2.4 Design precipitation sequence

The entire catchment area is in region 2. A precipitation sequence according to Table 3 is applied. The design value for day 9 is 120 mm. The average elevation of the catchment area is 820 m above sea level, implying (according to Table 4) that the sequence is elevation corrected by + 32.0 %. The catchment area is 1167 km^2, implying (according to Figure 4) that the area correction is 98.3 %. Following corrections, the maximum 24 hour precipitation is 156 mm.

8.2.5 Design flood calculation

The design flood calculation is based on climate data for the period 1982-1991. A time-step of 24 hours is used when running the precipitation sequence. The starting point water level is assumed to be + 466.14, implying that the reservoir is practically empty (0.14 m above minimum level). The continuous change of the seasonal correction, according to Figure 5, as well as the adjustment of temperature and precipitation according to section 5.11, are automatically handled by the model programme.

8.2.6 Results

The design flood is an autumn one occurring in August 1987 (Figure 7). The largest inflow as well as the highest water level occur when the flood design sequence is placed over the days of August 7th to 20th. This means that the heaviest precipitation (156 mm) falls on August 15th.

The largest inflow to the reservoir will be 675 m^3/s, occurring on August 16th, and the largest discharge occurs on August 17th at 560 m^3/s. The water level in the reservoir will reach a maximum + 493.51 on August 17th, implying that the maximum water level is surpassed by 0.61 m.

The design flood calculation is documented according to the compilation in Table 5.

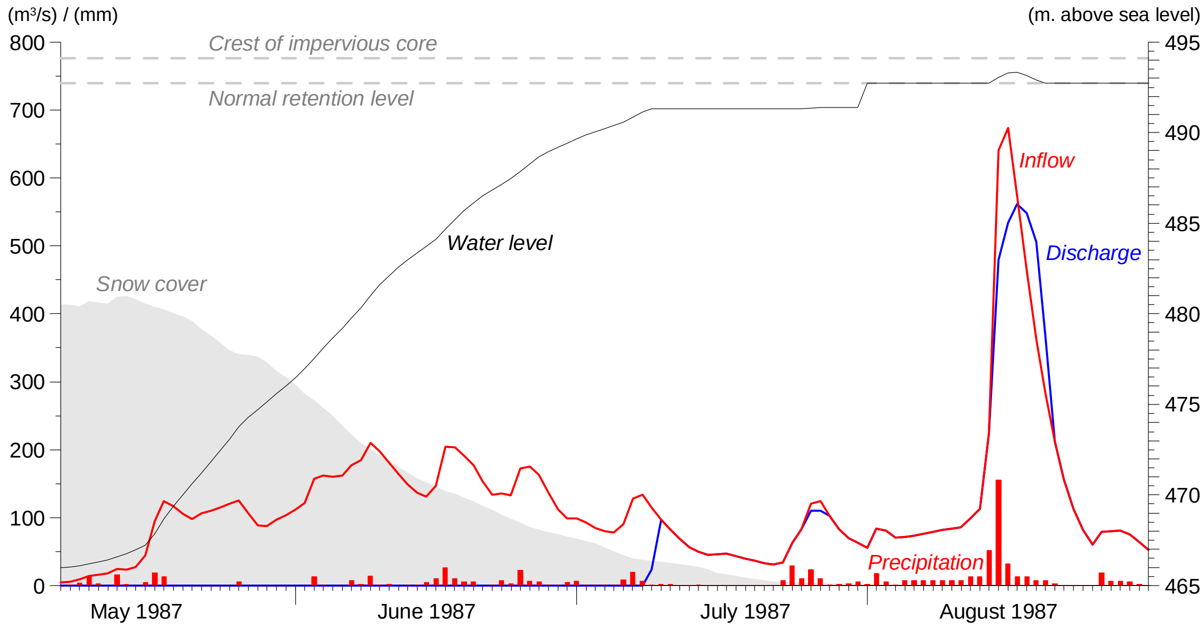


Figure 7. Design flood calculation for the Håckren dam.

8.2.7 Analysis

The calculations show that the normal retention level is surpassed by 0.61 m at the design flood, but that there is a margin to the top of the impervious core. The design flood maximum level is 0.79 m lower than this and 4.29 m below the dam crest. The results are analyzed following a consideration of waves and a wind set-up of the surface due to winds. Calculations of wind influence in this case results in an increase of the water level by 5 cm.

The conclusion is that the dam can withstand and pass a design flood of Flood Design Category I.

A check is also made of the capacity of the dam to discharge a flood of a 100 years return period at the normal retention water level. Using frequency analysis of inflow data, the 100 year flood is determined to be 333 m^3/s. Since the discharge capacity at the normal retention water level is 450 m^3/s, the dam complies with the criterion that it must be able to pass an incoming flood with a return period of at least 100 years at the normal retention water level.

Because of uncertainties as to the availability of the existing spillway at the Håckren dam, it has been decided to provide the dam with a new spillway, to increase safety even more (see Figure 8).

Table 5. Documentation of design flood calculation at the Håckren dam.

Dam data	
Coordinates (RAK)	701054 - 139011
Catchment area	1167 km^2
Catchment area average elevation	820 m. above sea level
Regulation data, discharge capacity	see separate document
Model data	
Model	HBV model, version; see separate document Time-step: 24 hours
Structure	Sub-area division, parameters, station data; see separate document
Model calibration	
Calibration period	1982 - 1991 (r^2 = x; acc diff = x)
Verification period	1973 - 1981 (r^2 = x; acc diff = x)
Calibration made yyyy-mm-dd	Name Surname, Company
Snow calculation	
Calculation period	1973 - 1991
Maximum water content	419 mm (May 2nd 1976)
30 years snow cover (Gumbel distribution)	414 mm
Latest date of snow maximum	May 6th (1981)
Precipitation sequence	
Region	100 % in region 2
Elevation correction	132.0 %
Area correction	98.3 %
Design information	
Model structure	Total flood design for entire catchment area, i.e. sub-areas Ottsjön and Håckren, regulation table; see separate document
Initial conditions	No x May 7th (414 mm snow, water level + 466.14 m above sea level)
Calculation period	1982 - 1991
Sequence time-step	24 hours
Results, flood design calculation	
Spring case (not designing):	Sequence start: July 8th
Maximum inflow	695 m^3/s (July 17th 1987)
Maximum discharge	520 m^3/s (July 19th 1987)
Maximum water level	+ 493.32 m above sea level (July 18th 1987)
Autumn case (designing):	Sequence start: August 7th
Maximum inflow	**675 m^3/s** (August 6th 1987) hydrograph; see separate document
Maximum discharge	**560 m^3/s** (August 17th 1987) hydrograph; see separate document
Maximum water level	+ **493.51 m. above sea level** (August 17th 1987) time series; see separate document
Maximum precipitation in the sequence	156 mm (August 15th 1987)
Calculation yyyy-mm-dd	Name Surname, Company
Checked yyyy-mm-dd	Name Surname, Company

Figure 8. On-going reconstruction to provide the Håckren dam with a new spillway to upgrade the discharge safety. (Photo: Vattenregleringsföretagen, 2006)

8.3 Design flood calculation at a dam in Flood Design Category II

In this example, a flood design calculation is carried out for the hydropower dam at Bålforsen in river Umeälven. The facilities are located some 90 km downstream of lake Storuman and consists of a concrete dam and a power station, operational in 1958. The reservoir is utilized for short-time regulation at a 24 hour basis. All discharge, up to a maximum of 315 m^3/s, is usually passing through the hydropower station. When more discharge is required, the water passes spillways with a capacity of discharging a total of 2220 m^3/s at normal retention water level.

8.3.1 In-data

In this case the analysis could be based on measured water flow data, since the reservoir volume is small and the discharge at high flows more or less equals the inflow. A period without major changes in the extent of regulation is chosen for the analysis. Water flow data during the 1969-2006 period will present 38 years of registered peak water flow values (Table 6).

Table 6. Yearly peak water flow (Q_{max}) at Bålforsen during 38 years, 1969-2006.

Year	Q_{max} (m^3/s)	Year	Q_{max} (m^3/s)
1969	245	1988	311
1970	296	1989	469
1971	305	1990	712
1972	805	1991	334
1973	461	1992	412
1974	302	1993	1215
1975	299	1994	302
1976	301	1995	525
1977	303	1996	305
1978	299	1997	549
1979	301	1998	877
1980	300	1999	306
1981	901	2000	888
1982	299	2001	786
1983	401	2002	312
1984	303	2003	279
1985	811	2004	841
1986	308	2005	312
1987	924	2006	309

8.3.2 Frequency analysis

A frequency analysis is carried out on peak water flow values during 38 years. The distribution functions Lognormal, Gumbel and Gamma (all with 2 parameters) are adapted to the data series (Figure 9).

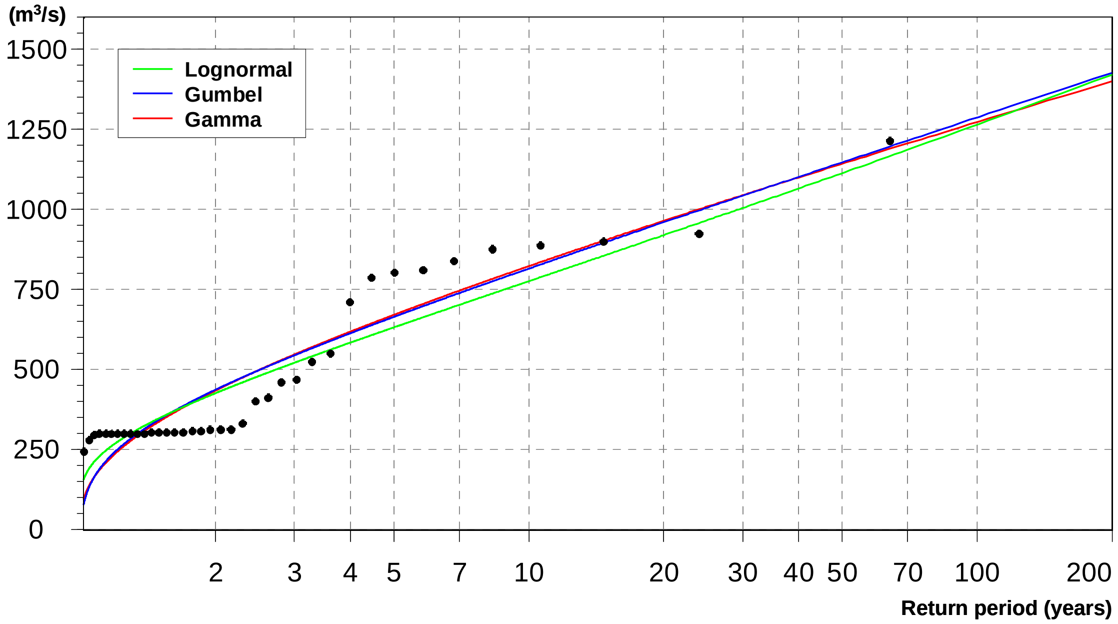


Figure 9. Frequency analysis of yearly peak water flow at Bålforsen.

8.3.3 Results

The different distributions functions in this case present a similar design flood with a 100 year return period (Table 7).

Table 7. Design flood at Bålforsen calculated with different frequency distribution functions.

	A 100 year return period flood (m^3/s)
Lognormal	1265
Gumbel	1287
Gamma	1273

8.3.4 Analysis

The results show that the discharge capacity of the dam at 2220 m^3/s surpasses 100 years return period floods with an adequate margin, whichever of the three distribution functions is used. A comparison with design flood calculation in accordance with Flood Design Category I shows that the dam is capable of passing this flood as well (2080 m^3/s). Considering existing discharge capacity and regulating routines, the water level would then be at normal retention water level. The conclusion is that the Bålforsen dam complies with the requirement according to Flood Design Category II to be able to pass an incoming flood with a return period of at least 100 years at the normal retention water level. In this case a cost-benefit analysis to determine a suitable higher flood is superfluous, since the margins are so great as to make the dam able to also pass a flood according to Flood Design Category I.

It should be added that the above example of a design flood calculation according to Flood Design Category II is rather uncomplicated. Regulation often makes it difficult to produce a suitable and homogeneous series of measurements for the analysis. It is important that the series to be analyzed is chosen as to be representative of the regulated conditions. The difference between the different distribution functions of Figure 9 is small, facilitating the conclusions. Usually this difference is much bigger, requiring consideration as to which distribution function would give the best description of the observed data.

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