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Resources Engineering

DAM SAFETY IN A HYDROLOGICAL PERSPECTIVE– CASE STUDY OF THE HISTORICAL WATER SYSTEM OF SALA SILVER MINE

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ABSTRACT

The old water system in Sala, formerly belonging to the silver mine, is analysed with regard to dam safety focusing on the hydrological aspects. The hydrological safety of the risk class I dams in the area, built in the 16th century, is not considered adequate according to the Swedish guidelines for design flood determination. A review is made of international principles for design flood determination. The overview shows that there is no common principle used internationally when dealing with design flood for dams. In some countries there is an ambition to implement risk assessment for evaluation of hydrological safety. However, at present Australia is the only country that has fully integrated risk assessment in their design flood guidelines. A risk assessment of the water system in Sala shows that neither increasing the spillway capacity nor implementing flood mitigation measures in the watershed have any significant effect on dam safety in the area. Nothing indicates that watersheds with a high presence of mires, like in the Sala case, should be particularly well suited for implementing flood mitigation in the watershed as a dam safety measure. In order to safely handle the design flood in Sala and avoid dam failure due to overtopping the flood needs to be diverted from the water system.

Key words: dam safety; design flood; flood mitigation; hydrological; risk assessment

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PREFACE

This thesis is based on the following manuscripts, reports and conference proceedings:

1. Fridolf, T. (2004)
   Hydrological dam safety (Manuscript)

2. Fridolf, T. (2004)
   Dam safety evaluation in Sala (Manuscript)

3. Fridolf, T. (2003)
   Hydrologisk modellering av Sala Silvergruvas vattensystem (Report)

4. Fridolf, T. (2001)
   Dam Safety Evaluation in Sala, Sweden (Proceedings from the conference "Safety, Risk and Reliability – Trends in Engineering, Malta 2001)

5. Fridolf, T. (2001)
   Design flood for dams – analysis of the Swedish guidelines (Proceedings from the ICOLD European Symposium, Norway, 2001)

1 INTRODUCTION

1.1 Background

This licentiate thesis was initially planned to deal with weather loads on dams in combination with risk analysis. But the research has instead focused on hydrological loads on dams. The reason for this was an opportunity to carry out an interesting case study concerning hydrological dam safety.

In the city of Sala, located in the central part of Sweden, 110 km west of Stockholm, silver mining was going on for many centuries and in order to secure the supply of waterpower needed for the mining, an extensive water system with dams, canals and regulations were implemented. When the municipality of Sala took over the water system in 1989, it became clear that the dam safety did not comply with the Swedish guidelines for design flood determination. The special features of the dams in Sala indicated that it would be an interesting case study to perform an evaluation of the hydrological dam safety in the area. Although the dams differ from conventional hydropower dams similar questions arise when evaluating the safety of small and medium hydropower dams where a dam failure would pose a risk to a few human lives.

Figure 1.1. ***Location of Sala***

1.1.1 Safety and risks

Several different definitions of risk can be found. The definition used here is taken from Berntsson´s "Dam safety and risk management" (Berntsson 2001) that follows the Canadian standard.

Risk is defined as a measure of the probability and severity of an adverse effect to health, property or the environment. The risk can often be calculated as the product of the probability and the consequences of the undesirable event, $R = P \cdot C$.

1.1.1.1 Society and safety

What is the objective of society when dealing with risks and safety and what is done in order to fulfil the safety demands? How are different risks valued in relation to each other?

One way for society to handle safety would be to use all available resources in such a way that statistically saves as many lives as possible. Society has however other aspects to consider besides the direct risk criteria when dealing with safety. Figure 1.2 shows different influencing factors on societies management of safety and risks.

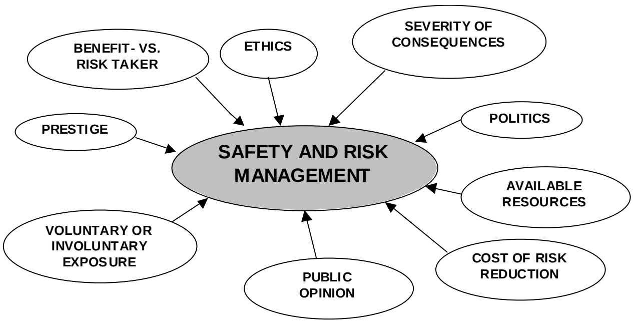


Figure 1.2 ***Factors influencing the way society handles safety and risks***

High probability-low consequence events versus low probability-high consequence events

Risks can be divided in "normal" risks and catastrophic risks. Normal risks are risks with a rather high probability and with modest consequences like for instance traffic accidents. Catastrophic risks on the other hand refer to risks with a very low probability but where the consequences are on a very large scale. A meltdown at a nuclear power plant or a dam failure of a large dam are typical examples of catastrophic risks.

Normal risks can be evaluated methodically comparing risks and costs for risk reduction in order to find the most effecient measures for increasing safety. But is it relevant to use this approach when dealing with low probability, high consequence events as well? Or should the objective be to avoid catastrophic risks at any cost? With traditional risk analysis methods the expected risk of low probability, high consequence events can be quite small and if society were to base their decisions exclusively on results from risk analyses a larger amount of money would probably be spent on high probability-low consequence risks like smoking than is the case today.

There is however a risk aversion against catastrophic risks and this is also reflected in the Swedish dam safety guidelines where the consequences weigh much heavier than the probability of dam failure. This probably leads to a poor use of available resources.

Benefit- versus risk taker and voluntary versus involuntary exposure

It is not always that the one benefiting from an activity is also the one being exposed to the risk from the activity. When driving a car the same person that benefits from the drive is exposed to the risk. The same counts for smoking where the smoker is the one enjoying the smoke but also the one most exposed to the risk. Besides, the car driver and smoker expose themselves voluntarily to the risk. In dam safety though the ones benefiting are the dam owner and the consumers of electricity, whereas the risk takers that are involuntarily exposed to the risk are the ones living downstream the dam.

Available resources and cost of risk reduction

Available resources and cost of risk reduction affect the way risks in society are handled. Society has to deal with an endless number of risks. Health risks, traffic risks, risks with nuclear power, military risks, risks of natural disasters etcetera and due to limited resources trade-offs between different risks are made.

Ethics

Ethics affect the way risks are handled. Although it does not necessarily lead to cost-effective decisions on risk management the question of ethics must be considered specially when it comes to loss of human lives and damages on the environment.

Politics, prestige and public opinion

Politics, prestige and public opinion affect many decisions made by society and risk management is not an exception. The null vision for deaths in the traffic that was presented some years ago clearly was not based on pure risk criteria. And when it was decided to permanently close one of the two reactors at the nuclear power plant Barsebäck in 1999 the discussion was based more on politics than on the actual risks.

1.1.2 Dam safety

Assessing dam safety is for several reasons a most important issue since dam failures can be very devastating for society. Likewise, implementing dam safety strategies is a complex task. One aspect is that dam failures fortunately do not occur very often. This causes obvious restrictions in applying statistical analysis since there is not much statistics to rely on. Besides every single dam is unique – primarily due to site-specific interaction between dam structure and dam foundation – meaning that every dam has to be analysed individually. Another aspect is that environmental impacts and forces are highly involved in dam safety. And it is very difficult to predict the behaviour of nature. A question of current interest is whether a climate change will have a significant impact on management of water resources systems in the future. When dealing with dam safety it is important to remember that nature cannot be fully controlled. Instead we have to adjust ourselves, society and engineering to the conditions of nature and use a risk strategy based on mitigation of the adverse effects instead of control.

Since very few new dams are built in Sweden today, the possibilities for young engineers to get practical experience from dam construction are limited. This makes the future management of existing dams in Sweden a problem of maintaining high quality of dam safety efforts. The older the dams get the more pronounced is the need for knowledge on how to deal with dam safety issues.

Our highly developed society is in many aspects more vulnerable than before. Almost every day we see examples of this – computer virus attacks, power failure, the fast spreading of foot-and-mouth disease, flooding with catastrophic losses, terrorist attacks etcetera. This increased vulnerability can also be applied to the issue of dams and dam safety. In order to reduce costs for operation and maintenance of dams surveillance- and warning systems have been installed. Operation is centralised to a few control stations from where the spillway gates are remotely operated. This has led to reduced costs and possibilities to better surveillance of selected functions but at the price of increased vulnerability. If the power transmission is struck out during a storm several dams can be affected at the same time. And sabotage can easily hit several dams. Dam maintenance nowadays is often purchased in competition and consequently it is becoming more and more common that maintenance is done by others than the personnel of the dam owner. In earlier days every major dam had its own staff that knew "their" dams very thoroughly and could act quickly during an emergency situation. The development with an infrastructure that tends to be more complex and vulnerable to disturbances will not stop. When considering the safe performance of dams it is necessary to consider that the consequences of a dam failure may change in the future.

1.1.2.1 Dam safety during the lifecycle of a dam

During the lifecycle of a dam the physical functioning of the dam, the loads and the safety requirements change and the technical knowledge increases. The safety management of dams is thus a continuous process and just because a dam once has been evaluated as sufficiently safe it does not mean that it can be considered safe in a longer time perspective.

During its lifetime a dam undergoes different phases:

1. Dam site selection and preinvestigations
2. Design
3. Construction
4. First filling
5. Operation
6. Decommissioning

The hydropower dams in Sweden are today in the operation phase and at present it is not likely that any new larger dams will be built, at least not in the nearest future. The phase of decommissioning though might come in question in the future if for different reasons it is no longer of interest to operate a dam. If for economical, technical, environmental or other reasons it is considered impossible to obtain a tolerable risk level at a specific dam, decommissioning may be the only option.

Most dams in Sweden were built during the 1950s, 1960s and 1970s (Bartsch 1995) whereas some were built already in the beginning of the 20th century. Documentation from the design and construction phases is often not complete which makes it difficult to predict the behaviour of the dams.

How does the safety of a dam change during the different phases? One aspect is that different dam engineers are involved in the different stages. In Sweden today the major part of the ones involved in the design and construction of the dams are retired. And if the design and construction are not well documented the knowledge of the intended functioning of the dams and how the dams were actually built will gradually be lost. On the other hand the amount of data increases during the lifetime of the dam. Monitoring and observation gives a better knowledge on the performance of the dam as time passes. And more data on the surroundings like flood observations, are obtained.

Personal experience from dam construction in general and from design and construction of the individual dam in particular decrease whereas performance data increase during the life cycle of a dam. The conclusion must therefore be that better methods for utilizing existing data in a systematic way for use in dam safety management must be developed. The further development and use of risk analysis is therefore essential when dealing with dam safety.

It is in this respect very important that data on dam performance and incidents is easily accessible for people working with dam safety management. During the work with this thesis the importance of easily accessible data was made clear to me. In this field we could probably learn from the United States where published reports and other information and data on dam safety are made public and easily accessible via Internet.

1.1.3 Risk analysis

As mentioned before *risk* can be defined as a measure of the probability and severity of an adverse effect to health, property or the environment. Even if the perception of risk is not a purely objective phenomenon but involves a high portion of subjectivity a systematic procedure for evaluation and management of risks is crucial and here risk analysis can be an efficient tool.

The definitions of risk analysis and risk assessment used here are taken from Berntsson´s "Dam safety and risk management" (Berntsson 2001) that follows the Canadian standard.

Risk analysis is defined as the use of available information to estimate the risk to individuals or populations, property or the environment, from hazards.

Risk assessment is defined as the process of deciding whether existing risks are tolerable and present risk control measures are adequate.

Risk analysis is a systematic approach to estimate the risk by the use of available information. The estimated risk is then evaluated to decide if it is acceptable or not. If it turns out to be unacceptable, risk reduction measures are implemented.

A risk analysis includes evaluation of probabilities for relevant failure modes as well as a consequence analysis. In order to estimate the probabilities statistical data can be used like data on traffic accidents for instance. But sufficient statistical data is not always available. In the field of dam safety the facts that dam failures fortunately do not occur very often and that every single dam is unique cause obvious restrictions in applying statistical data. In these cases subjective, degree-of-belief estimations of the probabilities based on expert judgement can be used. The consequences can also be difficult to estimate, especially when dealing with risks including loss of lives. Risk is in other words not an absolute, objective measure which makes the estimation of uncertainties an essential part of a risk analysis.

Risk analysis is a well-established technique for instance in the nuclear power industry, process industry and air industry. In the field of civil engineering however there seems to be a reluctance towards using risk analysis. Maybe because civil engineering is such an old field of engineering that to a large extent is based on experience.

1.1.3.1 The use of risk analysis in dam safety

The use of risk analysis when evaluating dam safety has until now only been used to a limited extent in Sweden as well as abroad. The development of risk analysis for dam safety seems to have reached farthest in Canada and Australia. Up today Australia is the only country that has fully integrated risk assessment in their design flood guidelines (ANCOLD 2000). The United States, South Africa and the Netherlands are other countries were risk analysis in dam safety is in full progress. In Sweden a few pilot studies have been performed and at Vattenfall a risk assessment methodology for dam safety management of their dams is under development.

Figure 1.3 describes the process of risk management for dams.

Risk analysis methods suitable for evaluation of dam safety are FMEA (Failure Modes and Effects Analysis), event tree analysis and fault tree analysis. For a detailed presentation of these methods refer to risk analysis literature, like (Rausand 1991).

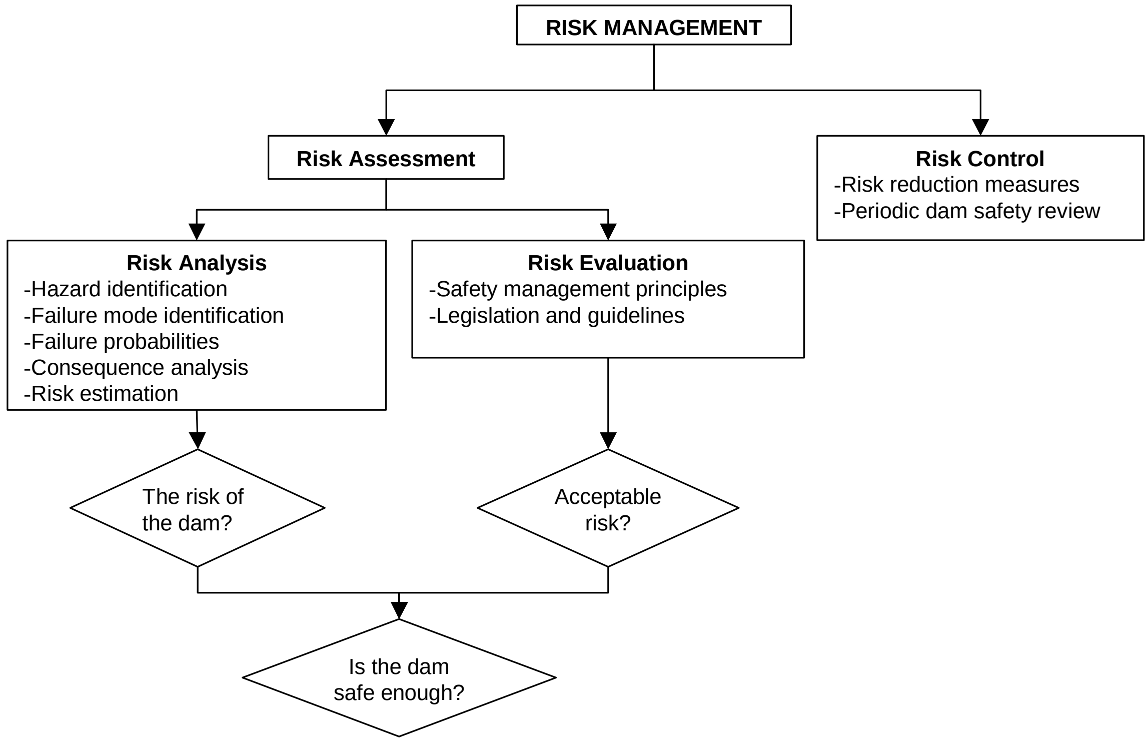
The use of risk analysis when dealing with dam safety has been criticised because factors that cannot be measured in economic terms are involved. And it requires estimation of the frequency of very unusual and extreme events. Another argument against the use of risk analysis is that it may be expensive to use due to the complexity of the method. At the one hand it is for small and middle sized dams that risk analysis could be an alternative to conservative design guidelines but on the other hand it is probably only at the large Swedish dams that the dam owner can afford to perform a complete quantitative risk analysis. It is also a fact that in Sweden so far, we have not experienced any major problems with dam safety so the question why risk analysis is necessary now when we have managed well without it before may arise.

However one can adjust the level of detail of a risk analysis depending on the purpose and available data and resources. It can range from qualitative descriptions of risk to detailed quantitative analysis. As more data becomes available the risk analysis can be developed to be more and more quantitative and detailed.

The economical resources available for dam safety improvements are limited and different dams and different safety measures have to be prioritised. Risk analysis can be used to see which risk reduction measures would have the largest effect on the risk posed by the single dam. Risk analysis can also be used to give priority among a portfolio of dams when implementing risk reduction measures. The use of a risk approach including risk analysis can thus be a way of securing effective use of available resources.

In order to facilitate and improve the use of risk analysis it is important that all available statistics are used. It is therefore crucial that incidents are documented by the dam owner and made easily accessible for people working with dam safety management.

Risk analysis is not a method to obtain an absolute measure of dam safety. Rather it should be seen as a complement to engineering judgement and present design principles and be used in a comparative way. However research in the area is in full progress and since we are only in the beginning of practising risk analysis when dealing with dam safety it is reasonable to expect changes in the application.



Figur 1.3 ***Description of the risk management process for dams, based on (Kreuzer 2000)***

1.1.4 Hydrological dam safety

The most common causes of failure of embankment dams according to international statistics (ICOLD 1995) are:

- Overtopping 32 %
- Internal erosion 27 %

Overtopping is connected to the hydrological load of the dam, directly through an extreme flood or indirectly by malfunction of the discharge facilities. The hydrological load is the combined effect of the magnitude and duration of the flood, precedent storm events, the initial water level in the reservoir at the start of the flood and the discharge capacity of the dam.

In order to decrease the probability of overtopping either the functional capacity of the dam can be changed like increased discharge capacity or the basic conditions affecting the hydrological load can be changed.

Nature and its properties is not an exact science. We do not know for sure how nature will evolve in the future and there is no exact answer on how high a flood can be. To what extent should this uncertainty be taken into consideration when making the dam safety requirements? Should we for example already consider the effects a possible climate change could have on dam safety by adding safety factors or should we wait until we know for sure? No matter what, it should be obvious that the dam safety work is a changing and continuous process. The question is how far in the future one should be looking when the hydrological safety of a dam is evaluated?

The principle used in Sweden today for managing the hydrological dam safety is based on evaluating the ability of the dams to safely handle a calculated extreme flood, see figure 1.4.

A risk approach on the other hand considers different floods in combination with other factors producing different flood scenarios. The risks posed by the different flood scenarios are estimated and evaluated to determine if they are acceptable or not. If they turn out to be unacceptable, risk reduction measures are implemented, see figure 1.5.

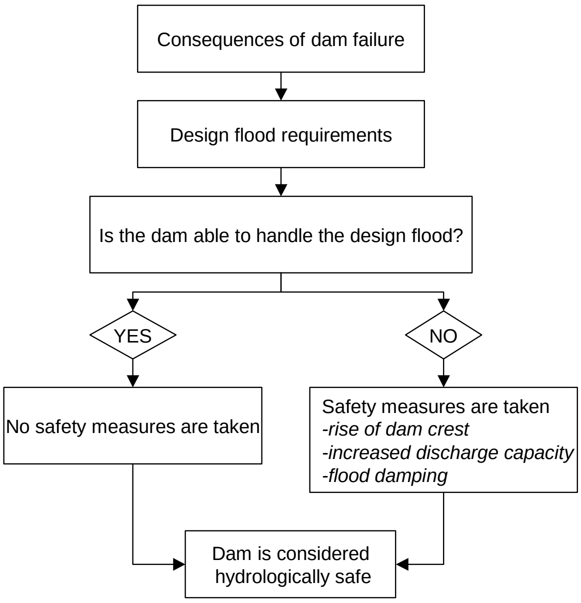


Figure 1.4 ***Management of hydrological dam safety in Sweden today***

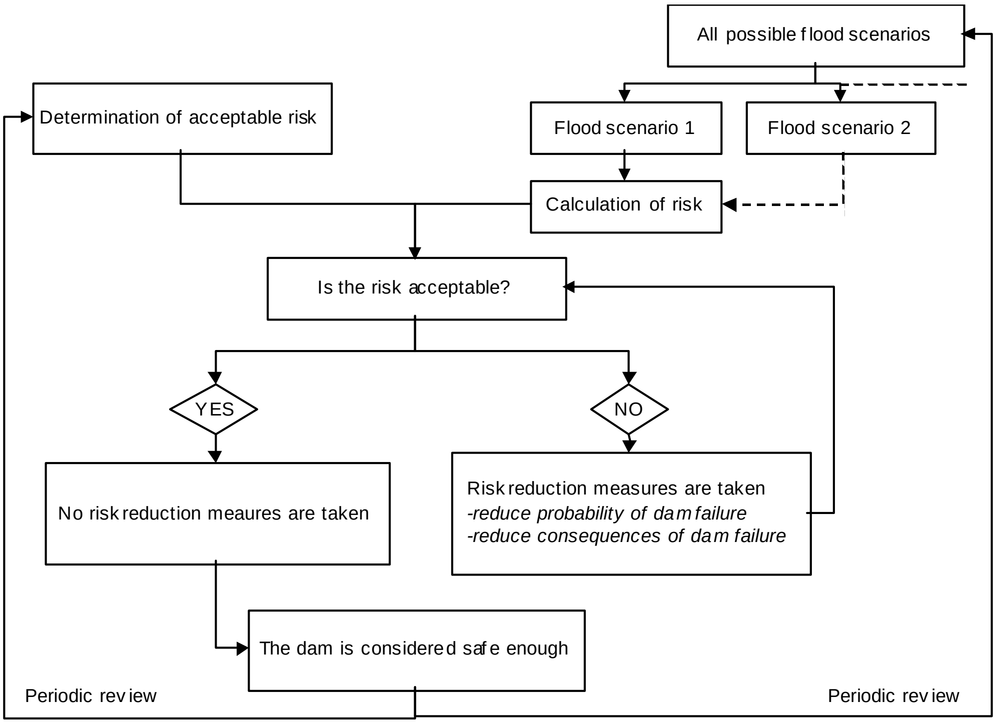


Figure 1.5 ***Management of hydrological dam safety with a risk assessment approach***

1.1.4.1 Design flood determination

Connected to the hydrological load of the dam is the concept of design flood. There are different methods for determination of the design flood.

The flood frequency methods are based on a statistical evaluation of historical flood observations. Distribution functions are fitted to observed extreme values and extrapolated to the desired return periods. Flood frequency analysis is simple to apply and specifies the return period of the flood. The problem is that the probabilities in question when dealing with extreme floods are so small. A rule of thumb is that return periods exceeding the double observation period is unreliable (Killingtveit et al. 1995) and in most countries the longest available runoff records are at a maximum about 100 years long.

Another design method is to maximise the runoff generating factors like precipitation, soil moisture and snow melt and convert these factors to a flood by the use of a hydrological model. The use of hydrological models for determination of design flood can be based on the actual hydrological characteristics of the watershed and it is possible to adjust the model to changes that occur in the watershed. It is however difficult to determine unique parameter values since the model can function with "wrong" parameter values, calibration for moderate or high observed floods may not be valid for extreme floods and the return period of the resulting modelled flood is unknown. Rainfall/runoff analysis is used to calculate the Probable Maximum Flood, PMF. PMF is defined as "*the largest flood to be expected assuming complete coincidence of all factors that would produce the heaviest rainfall and maximum runoff*". The PMF is a theoretical flood that has no direct connection to actual conditions and the concept of PMF may lead to the false impression that it is a flood that cannot be exceeded.

1.1.4.2 Risk analysis as an alternative to design flood determination

Instead of looking separately at the hydrological load of the dam, risk analysis can be used to integrate the hydrological and hydraulic characteristics with the overall safety factors of the dam. A risk analysis may for instance reveal that a relatively modest flow in combination with some other unfavourable conditions like blockage of the spillway by debris poses a larger risk to the dam than an extreme flood in itself. The use of risk analysis makes it possible to take the special features of the individual dam into account. In order to facilitate and improve the use of risk analysis it is important that all available statistics are used. Rain and flood statistics should be easily accessible as well as data on dam performance during different flooding situations.

1.1.4.3 Swedish guidelines for design flood determination

In 1990, the Swedish Committee for Design Flood Determination presented a report with guidelines for determining design floods for dams.

The dams are divided in classes based on the potential consequences in case of dam failure, risk class I and II where dams in class I constitutes the highest risk defined as a non-negligible risk to human life or other bodily injury or a clear risk of major economic damage. The design flood for dams in risk class I shall be simulated by applying an accepted hydrological model using a combination of unfavourable meteorological and hydrological conditions. For dams in risk class II the design flood should be the flood with a return period of 100 years, determined by frequency analysis. The Swedish guidelines use a deterministic approach for high-consequence dams comparable with the concept of PMF. Though the Swedish method is based on a critical timing of the flood generating factors which have all been experienced but not at the same time or place. When calculating

PMF on the other hand, the precipitation is usually increased to values exceeding the observed precipitation.

A 14-day sequence of rainfall data based on the highest observed area precipitation over an area of 1000 km^2 with adjustments for time of year, region and area is combined with specified snow melt and soil moisture conditions to produce the design flood. Regulation strategies and wind impact is also considered.

1.1.5 The Sala water system

The water system in Sala is a small-scale system consisting of lakes, dams, gated discharge facilities and channels. The oldest dams where built already during the 16th century and are classified as historical monuments, meaning that the alternatives for major reconstructions are restricted. The dams consist of long earth walls just a few metres high and often covered with trees. At several places where water used to be stored the discharge facilities have been removed, see figure 1.6. Today the water system has a great value as a recreational area and as a historical monument.

There are five major lakes/reservoirs, Storljusen, Harsjöarna, Silvköparen/Olov Jons dam and Långforsen. Olov Jons dam and Långforsen have been classified as class I dams.

The area contributing with runoff to Långforsen is approximately 84 km^2 and the total available storage volume of the water system has been estimated to about 16 millions m^3 (Sundholm 1932).

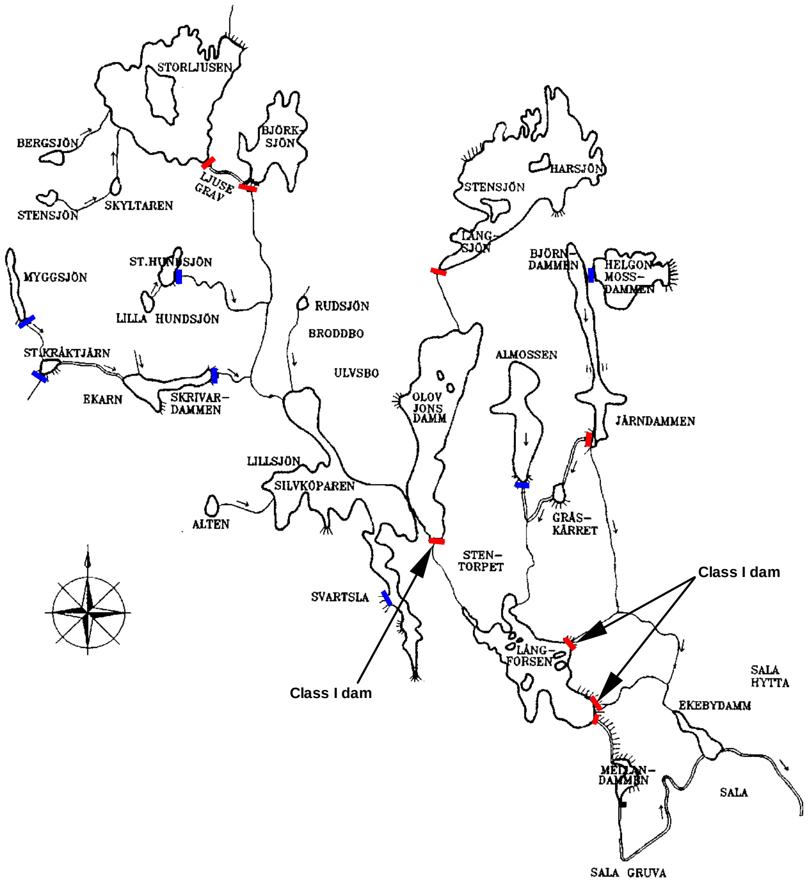


Figure 1.6 ***The water system of Sala. Present regulation facilities are marked with red whereas removed regulation facilities are marked with blue.***

2 OBJECTIVES

The overall objective of the thesis has been to find a reasonable strategy for handling the hydrological dam safety in Sala. The following activities have been central to the study:

- Analysis of how the hydrological loads affecting a dam can be reduced, with focus on the advantages and disadvantages of implementing local flood mitigation in the watershed
- An international overview of design flood principles for dams and comparison with the Swedish guidelines for design flood determination
- Hydrological modelling of the water system of Sala before and after implementation of flood mitigation measures. Besides the design class I flood, the resulting floods from 5-, 10-, 30- and 100-year rains determined by frequency analysis have been modelled
- Risk assessment of the dam safety in Sala with focus on the hydrological aspects

3 MATERIAL AND METHODS

3.1 Literature studies

Literature studies have been performed in the field of dams, dam safety, hydrology with attention to high and extreme floods and risk analysis. Literature about risk analysis in connection with dam safety has been difficult to find and often one statement contradicts another. Accordingly this leaves much room for subjective judgments. The information is often on a general level and it is seldom information is found on how risk analysis should be applied in practice when dealing with dam safety.

3.2 Interviews

The international overview of design flood principles is based partly on literature studies and partly on interviews with persons working with design flood determination for dams in the respective countries.

3.3 Frequency analysis

In order to make an indirect estimation of the probability of flooding in Sala rain sequences with different return periods have been estimated and used as input for hydrological modelling of the watershed. The rain sequences have been determined by frequency analysis based on annual maximum precipitation values from the period 1961-2000 from a SMHI-station placed about 3 km southeast of Sala. The frequency distributions being used are the Gumbel-, Lognormal- and Log-Pearson type III distributions. The distribution parameters have been estimated by the method of moments and the goodness of fit has been tested by chi-square test.

3.4 Hydrological modelling

The hydrological model used for runoff simulation in Sala is HEC-HMS (Hydrologic Engineering Center - Hydrologic Modeling System). The model being a development of the HEC-1 model is developed by the US Army Corps of Engineers.

HEC-HMS includes different mathematical models for simulation of precipitation and runoff processes. Figure 3.1 shows the principles used for describing runoff in HEC-HMS. The models available in HEC-HMS are listed in table 3.1.

Below follows a description of the calculation methods chosen for modelling the water system in Sala. For a description of the other methods see the users manual of HEC-HMS (US Army Corps of Engineers 2001).

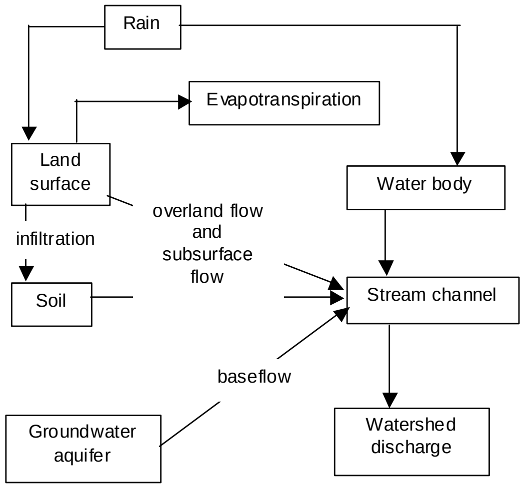


Figure 3.1 ***The principles of describing runoff in HEC-HMS***

Tabel 3.1 ***Available mathematical models in HEC-HMS***

RUNOFF VOLUME MODELS	DIRECT RUNOFF MODELS	BASEFLOW MODELS	ROUTING MODELS
Initial and constant loss rate	User specified unit hydrograph, UH	Constant, monthly	Lag
SCS curve number, CN	Clark´s UH	Exponential recession	Muskingum
Gridded SCS CN	Snyder´s UH	Linear reservoir	Modified Puls
Green and Ampt	SCS UH		Kinematic wave
Deficit and constant loss rate	ModClark		Muskingum Cunge
Soil moisture accounting, SMA	Kinematic wave		
Gridded SMA			

3.4.1 Modelling runoff volume

Runoff volume is calculated by computing the volume of water that is intercepted, infiltrated, stored, evaporated or transpired and subtracting it from the precipitation. The model used for the watershed in Sala is Deficit and constant loss rate. An initial loss, I_a, is added to the model to represent interception and depression storage. Until the accumulated precipitation exceeds the initial loss volume, no runoff occurs. If the watershed is saturated, I_a will approach zero. When there is no initial storage capacity left the loss of precipitation occurs at a constant rate, f_c.

$$pe_t = \begin{cases} 0 & \text{if } \sum p_i < I_a \\ p_t - f_c & \text{if } \sum p_i > I_a \text{ and } p_t > f_c \\ 0 & \text{if } \sum p_i > I_a \text{ and } p_t < f_c \end{cases}$$

pe_t = runoff volume at time t

p_t = precipitation at time t

f_c = constant loss rate

I_a = initial loss

The initial loss can recover after a prolonged period of no precipitation. HEC-HMS continuously computes the moisture deficit as the initial storage volume less precipitation volume plus recovery volume during precipitation-free periods.

3.4.2 Modelling direct runoff

For transformation of runoff volume to direct runoff Snyder's unit hydrograph has been used. The unit hydrograph is the runoff as a function of time for a rain with a specified duration and a uniform rainfall rate, usually 1 mm over the duration.

Snyder defined a standard unit hydrograph as one whose rainfall duration t_r is related to the basin lag t_p by $t_p = 5{,}5t_r$

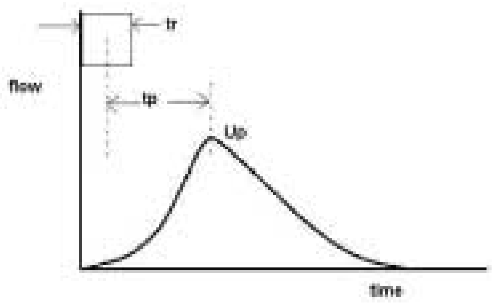


Figure 3.2 ***Snyder's unit hydrograph***

$$\frac{U_p}{A} = C_2 \frac{C_p}{t_p}$$

U_p = *peak of standard unit hydrograph*

A = *watershed drainage area*

C_p = *coefficient*

C_2 = *constant* = 2,75

t_p can be estimated as

$t_p = C_1 C_t (LL_c)^{0,3}$

C_t = *basin coefficient (determined by calibration)*

L = *length of the main stream from the outlet to the divide*

L_c = *length along the main stream from the outlet to a point nearest the watershed centroid*

C_1 = *constant* = 0,75

3.4.3 Modelling baseflow

Baseflow is the sustained runoff of prior precipitation that was stored temporarily in the watershed plus the delayed subsurface runoff from the current storm. For calculation of baseflow in Sala the Exponential recession model has been used.

$Q_t = Q_0 k^t$

Q_t = *baseflow at time t*

Q_0 = *baseflow at time t=0*

k = *exponential recession constant*

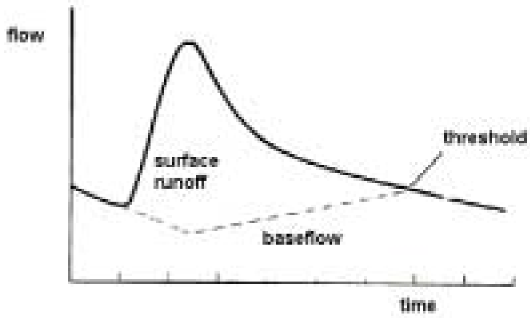


Figure 3.3 ***Relation between surface runoff and baseflow***

3.4.4 Modelling channel flow

For modelling channel flow in Sala the simple Lag model has been used. The inflow hydrograph is delayed by a lag time without any attenuation of the flow.

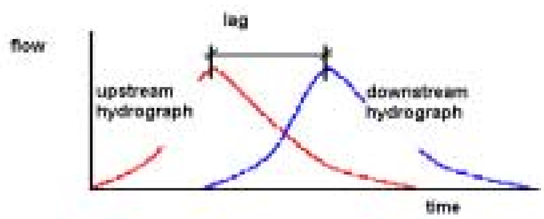


Figure 3.4 ***Principle of the Lag model***

3.4.5 Modelling reservoirs

Reservoir storage is described in HEC-HMS by the continuity equation:

$$\frac{I_t + I_{t+1}}{2} - \frac{O_t + O_{t+1}}{2} = \frac{S_{t+1} - S_t}{\Delta t}$$

I_t=inflow at time t

I_{t+1}=inflow at time t+1

O_t=outflow at time t

O_{t+1}=outflow at time t+1

S_{t+1}=storage at time t+1

S_t= storage at time t

Δt=time interval between t and t+1

3.4.6 Calibration and validation

Since continuous flow data over a prolonged period does not exist in Sala the automatic calibration alternative included in HEC-HMS has not been used. Instead calibration has been done manually by a graphical comparison of calculated and observed flows. The model has been calibrated for a rainstorm during the period November 1 – December 15 2000. The November flood 2000 is considered an upper limit of what the water system can handle in a safe way with present conditions.

The model has been validated for a rainstorm during the period April 12 – April 30 1999. It would have been preferable to use the same time of season for validation as for calibration but due to a limited amount of flood data that was not possible.

3.5 Dam break analysis

Dam break analysis for the dams of Olov Jons and Långforsen in Sala has been done according to the Dam safety guidelines of Washington State Department of Ecology (Washington State Department of Ecology 1992). For more sophisticated calculations a hydraulic model like DAMBRK or FLDWAV could be used. However based on the small size of the dams and the sparse data available, the simplified method has been considered sufficient in this case.

4 RESULTS

4.1 Measures for reduction of the hydrological loads on a dam

The hydrological situation in a river system is related to many factors such as climate, hydrological runoff characteristics of the watershed like topography, soil and vegetation features, land use and size and shape of the watershed, reservoir regulation strategies and spillway capacity. Consequently a change in one or more of these factors will affect the hydrological load on the dam.

4.1.1 Implementation of local flood mitigation measures in the watershed

To reduce the flood peaks the runoff can be attenuated over longer periods. This means primarily that more active storage volumes have to be created. In order to decrease the hydrological and hydraulic loads of the dam local attenuation of the runoff in the watershed like controlled inundation of flood plain areas, wetlands and forest areas can be implemented. The objective of flood mitigation in the watershed is to reduce the flood peaks by attenuating the runoff over longer periods.

More effective storage volume and increased time of concentration in a watershed can be created by:

- Controlled inundation of areas where the consequences of flooding are less severe like mires, fields and forests by constructing levees and discharge facilities
- Restoration of wetlands. Besides fulfilling a primary purpose of flood mitigation these wetlands can also develop a value as recreational areas and for promoting ecological diversity
- Clearing of existing watercourses and lakes

The time of concentration can be increased by:

- Blocking of the drainage systems of field or mires
- Restoration of the natural course of rivers that have been widened, straightened or made less permeable by for instance concrete lining

Below are listed some properties that are desirable for areas used for flood mitigation:

- Soils with high permeability and high porosity
- Vegetation with a high water absorption capacity
- Existence of natural embankments
- Existence of natural wetlands
- Possibility to construct discharge controlling facilities without too much efforts
- Small negative impacts of inundation
- Large non-developed areas

Benefits with flood mitigation in the watershed:

- The hydrological load is not only reduced for the dam but for the downstream area of the dam as well. It is a possible good example of integrated flood management leading both to increased dam safety and reduced flooding of downstream areas
- Water can be discharged from the watershed during dry periods
- It can be a rather cheap measure compared to rising dam crests, upgrading of existing spillways and construction of new spillways
- It can provide an alternative in case it might be impossible to make any structural measures on the dam in order to handle the safety. For instance in the water system of Sala there are restrictions on reconstructions since the dams are classified as historical monuments
- The flooding can be diverted to a place where it makes the least damage

Disadvantages with flood mitigation in the watershed:

- Negative consequences on the inundated area. Manmade inundation of some areas such as wetlands and forests may have a negative impact on the fauna
- For a class I design flood situation it is very large volumes of water that need to be stored for significant mitigation of flood peaks
- If a high flood that has been damped and stored is succeeded by another high/extreme flood the entire stored water volume may have to be released leading to an increased load on downstream dams and increased flooding consequences
- The effect on dam safety depends on the different runoff times for the flood components reaching the reservoir. Flood mitigation in the watershed should delay the different flood components. However this can also lead to a higher hydrological load of the dam if the delayed flood components are not dispersed and therefore tend to reach the dam simultaneously at a more critical time
- Flood mitigation in the watershed can lead to negative economic consequences if the mitigation causes environmental damages and reduced water for power production
- Flood mitigation in the watershed implies increased need for supervision and control

If the total water volume to be discharged during a flood is large, local flood mitigation is probably not a realistic alternative since large areas for inundation would then also be needed. The positive effect of local flood mitigation is therefore probably highest for short and intense rainfalls and for watersheds that initially have a fast runoff response.

Implementation of flood mitigation requires a thorough analysis of the whole watershed. It is important to analyse the possible effects on safety, environment and economy using a systems approach. A flood mitigation strategy as a successful dam safety measure is highly dependent on reliable weather and flood forecasts as well as reliable hydraulic models.

As a general dam safety strategy during floods it is in most cases probably wiser to release as much water as possible from the system instead of trying to store it in the watershed upstream. There should however be situations where local flood mitigation could be a suitable solution and there should be potential areas suitable for this measure in Sweden since we have many sparsely populated areas, especially in the north.

4.1.1.1 The use of mires for flood mitigation

The idea of using areas in the watershed upstream of the dam for local flood mitigation during high/extreme floods to promote dam safety was of particular interest to study in Sala due to a high presence of mires. If these wetlands create additional retention capacity - absorbing water during floods and releasing water during dry periods they would be very well suited for local flood mitigation. In order to get more knowledge of the hydrology of wetlands a literature study was performed.

Sweden is one of the countries in the world that has the highest portion of mires. About 10 millions ha or more than 20 % of the area is mires (Larsson). Available literature is primarily related to research carried out during 1972 to 1976 at two mires in Sweden, Komosse in Småland (Brandesten 1987) and Solmyren in Lappland (Jansson 1981).

The groundwater level is close to the ground surface during most of the year and the mires therefore practically always stay near face saturation. This means that small amounts of rain is sufficient to rise the water level to the surface or close to it. This in combination with the fact that the upper permeable part of the acrotelm is thin means that completely saturated areas producing surface runoff can expand very fast in mires (Burt et a. 1990). Consequently the storage capacity is limited.

It does not seem likely that mires are particularly well suited for flood mitigation. The groundwater level lies near the ground surface except during dry periods and the upper permeable layer is so thin that the storage capacity is limited and accordingly mires respond quickly to rain by producing surface runoff almost immediately. Instead of mitigating the flood peaks the mires probably increase them. There are however a variety of different types of mires and the damping capacity may differ from mire to mire. If the mires are thick and located in a depression in the landscape they can probably have a ponding effect and from a hydrological/hydraulic point of view be treated as lakes.

4.1.2 Flood diversion

To reduce the hydrological load on the dam the flood can be diverted away from the watershed in order not to reach the dam. Either the entire water flow or a part of it can be diverted. The benefit with flood diversion is that the total hydrological load of the dam can be reduced. The disadvantage is that diverting the water to a course it normally does not take can lead to negative consequences along the new watercourse.

There is a principal difference between local flood mitigation and diversion in the sense that local mitigation leads to a dispersion of the flood in time whereas diversion leads to a displacement of the flood in space. In the case of diversion, the water never reaches the dam contrary to local mitigation where the water eventually will reach the dam.

4.1.3 Reservoir regulation strategies

During the floods in Sweden in July 2000 the power industry was criticized for not taking enough consideration to safety aspects in their reservoir regulation strategies. An analysis of the floods during summer and autumn of 2000 and winter of 2001 states that the flooding could probably not have been avoided even with changed regulation strategies (Svenska Kraftnät 2001). The safety of the dams also has to be prioritized before flood mitigation for downstream areas since a dam failure could lead to catastrophic consequences.

A change in the seasonal pattern of floods with a decreased spring flood and an increase in the summer and autumn floods and possibility for high floods even during winter is a possible scenario according to climate studies. Late summer/autumn is the time when the storage capacity of the reservoirs are utilised. A high flood together with a full reservoir could lead to a hydrological load as high as one caused by an extreme flood when the reservoir is below full supply level.

A Spanish study (Andrés 2000) concludes that by keeping a part of the storage volume for safety purposes it is possible to considerably increase the safety factors. Keeping a part of the storage volume for safety purposes could lead to a loss in production incomes for the dam owner but in comparison with the costs for upgrading the dam to safely pass the design flood it may however be an interesting alternative in some cases. At least for dams where a dam failure will not cause catastrophic consequences. In a report on flood mitigation possibilities at Swedish dams (Rytters et al. 1995) the possibilities of creating effective storage capacity for flood mitigation using pre-spilling in order to decrease the demands on discharge capacity are discussed. The report concludes that in reality the possibilities to effectively use pre-spilling are very limited.

A change in the regulation strategies with a lower full supply level during autumn and winter could have an effect on flooding due to short, intense rains. When it comes to long lasting rains that can last for several weeks the effect of changed regulation strategies are however more uncertain since then it is likely that the reservoirs will be full at some point irrespective of the initial water level.

It is difficult to predict floods in advance and there is no guarantee that a high flood will not be succeeded by an even higher flood. For the large regulated river basins the whole system of dams interact. A change in the regulation strategy of one dam might lead to negative consequences for downstream dams. Besides, the regulation is controlled by the conditions provided by the environmental court. Changing the reservoir regulation strategies is therefore a complex task that requires extensive analysis in order to evaluate its overall effect on dam safety. This should however not be a reason for not looking over the old water laws that are written for a seasonal pattern where high floods mainly occur due to spring snowmelt. Changing the conditions given by the environmental court are a complicated, time consuming and costly process but in a long-term perspective it is probably necessary in some cases.

In the future applying optimal, multipurpose regulation strategies may be a crucial issue for water resources management of river basins around the world. In Sweden however the large rivers are regulated for hydropower production and multipurpose regulation strategies in these existing systems is probably very difficult to apply in practise. It should be easier to apply when it comes to constructing new dams. Besides the benefits are probably larger in countries with other needs for water management than Sweden, for instance countries with a water shortage and more extreme and recurring floods.

4.1.4 The spillway capacity of the dam

Increasing the spillway capacity is a way of securing that the requirements according to the guidelines for design flood are fulfilled. Increased spillway capacity can be obtained by either enlarging existing spillways, open up existing spillways that have been closed like spillways used for timber floating, or by constructing new ones. One solution is to install auxiliary spillways in the form of self-regulating fuse plugs.

A larger spillway capacity can lead to increased negative downstream consequences like erosion, flooding and increased load on downstream dams. It is therefore important to take into consideration the whole river system and thoroughly analyse the possible effects of an increased spillway capacity at a certain dam. At some dams it might be disproportionately complicated and expensive to increase the discharge capacity due to technical causes.

4.1.5 Rise of the dam crest

A rise of the dam crest is another way of securing that the design flood requirements are fulfilled. There is however some risks connected to a dam crest rise and these risks should be evaluated before the rise is done.

Possible risks are:

- A higher water level results in a higher hydraulic load on the dam. It is therefore important to control that the dam is able to handle a higher hydraulic load, even if it is for a short period of time
- A higher flood than the one used for designing the elevated dam crest may occur. If such a flood should occur a rise of the dam crest would lead to the release of an even larger water volume in case of a dam failure
- A rise of the dam crest might lead to a false sense of security and other safety measures might be neglected
- When performing the rise of the dam there is a possibility of disturbance of the existing dam, which might lead to a decreased safety. And during the modification of the dam construction accidents might occur. Graham (Graham 2000) states that *"modifying a dam that already has a very small chance of failure may increase overall risk to human life"*. This has also relevance when reconstructing spillways in order to increase the spillway capacity

4.1.6 Integrated flood management

It is not always possible to fully control floods and no flood defence structure can be designed for absolute safety. Instead a flood mitigation strategy can be applied where the risk of flooding is reduced as far as possible with reasonable means. It must be made generally recognized that living downstream a dam or close to a river involves a risk - a risk that may be mitigated but not totally eliminated.

When regulating a hydropower dam there is a conflict of interests. Figure 4.1 illustrates in a simplified way different objectives of reservoir regulation.

The aim of the dam owner is to:

- Run the dam for optimized power production
- Keep the dam sufficiently safe at a cost as low as possible

The aim of society, the public and those living upstream and downstream is to:

- Keep the dam safe
- Reduce upstream and downstream flooding

Superior to both power production and flood protection is the safety of the dam. However other relevant factors than dam safety should as far as possible be considered when dealing with flood management.

An aspect of the importance of integrated flood management that should have become obvious in Sweden during the flooding in 2000-2002 is the need to integrate the risk of flooding and dam failure in the physical planning process. Before the regulation of our rivers everyone was well aware of the risk of flooding along the watercourse and learnt to live with these recurring floods. But because the hydropower dams as a side effect provide a certain protection against flooding a false sense of security has arose and we easily forget that high floods is a natural recurring phenomena that can not be fully controlled. New developments in flood prone areas should not be allowed. And in the case of existing buildings and infrastructure in flood prone areas, often consisting of summer houses, a solution could be to move the houses. Compared to the costs for recurring flood damages and the costs for upgrading dams to safely handle a class I design flood it may turn out to be an economically sound solution. These flood prone areas could instead be converted to valuable recreational areas.

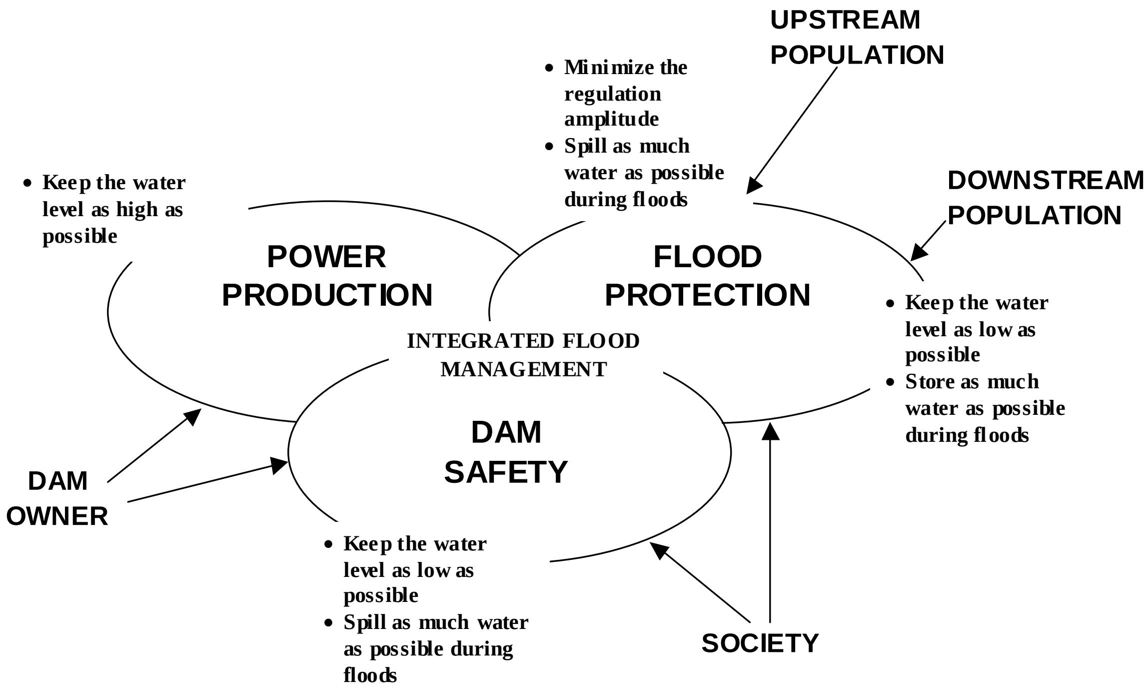


Figure 4.1 ***Different objectives of reservoir regulation***

4.2 Design flood – international overview

Of the countries studied Norway, the United States, the United Kingdom and Canada use the Probable Maximum Flood, PMF, as design flood for dams in the most serious risk class. The countries in Southern Africa use a design flood called the Regional Maximum Flood, RMF, based on over 500 observed maximum flood peaks.

Australia uses a risk-based approach where the overall dam safety is considered and not just the hydrological load. In the United States the Bureau of Reclamation already use risk assessment whereas the Army Corps of Engineers are currently developing probabilistic guidelines. In Canada and the Netherlands a risk-based approach is under development.

The other countries studied, Finland, France, Germany, Italy, Spain, Switzerland and the Czech Republic, use a design flood based on frequency analysis with a return period varying between 1000 years and 10,000 years. Some countries like Norway, Spain, Germany, Switzerland and South Africa make a distinction between the spillway design flood and the flood used for dam safety evaluation.

The Swedish design flood for dams in consequence class I can be compared to PMF. Though the Swedish method is based on a critical timing of the flood generating factors which have all been experienced but not at the same time or place. When calculating PMF on the other hand, the precipitation is usually increased to values exceeding the observed precipitation.

There is no common principle used internationally when dealing with design flood. Instead each country has its own way of handling the design flood. Some countries use probabilistic methods while others use deterministic methods and some use a different flood for design than for safety evaluation. For countries using probabilistic methods the return period of the design flood is in the range of 1000 to 10,000 years. Freeboard should be accounted for in some countries whereas in others no consideration is taken to it. And in some countries a higher design flood is required for embankment dams than for concrete dams. The comparison of design flood between different countries is thus ambiguous. Conditions like properties of watersheds and dams, climate and density of population living downstream differ between the countries and different cultures have different objectives and policy for handling safety and risks. Therefore it is probably not reasonable to expect common design flood guidelines to be developed that are applicable to all countries. The differences could also be seen as a reflection of the uncertainty connected to extreme floods. A common feature is that no country seems to make any significant distinction between new and existing dams.

4.2.1 Some aspects of the Swedish guidelines for design flood determination

The Swedish guidelines do not only consider the magnitude of the incoming flood but also take into account damping in the reservoir and to some extent regulation strategies and initial water level. Besides they consider wave run up and inclination of water level. According to the guidelines the water level in the reservoir should be assumed to have reached full supply level on August 1st at the latest. Depending on the actual initial water level when the flood reaches the reservoir this assumption provides an unknown additional safety margin.

To some extent a risk approach is used when dividing dams into consequence classes. However the classification only considers the consequences and not the probability of a possible dam failure. Besides the classification system is coarse which does not help the dam owner in his allocation of resources for dam safety measures.

To perform a complete calculation of class I floods in a river according to the guidelines is a resource demanding and complicated task.

Since the Swedish guidelines are deterministic they do not, unlike probabilistic methods, give an estimation of the probability of dam failure due to floods and they do not integrate the uncertainty. On the other hand the guidelines have the advantage that they can be adjusted to changes that occur like a change in regulation strategies or a possible climate change.

4.3 Hydrological modelling of the water system of Sala Silver Mine

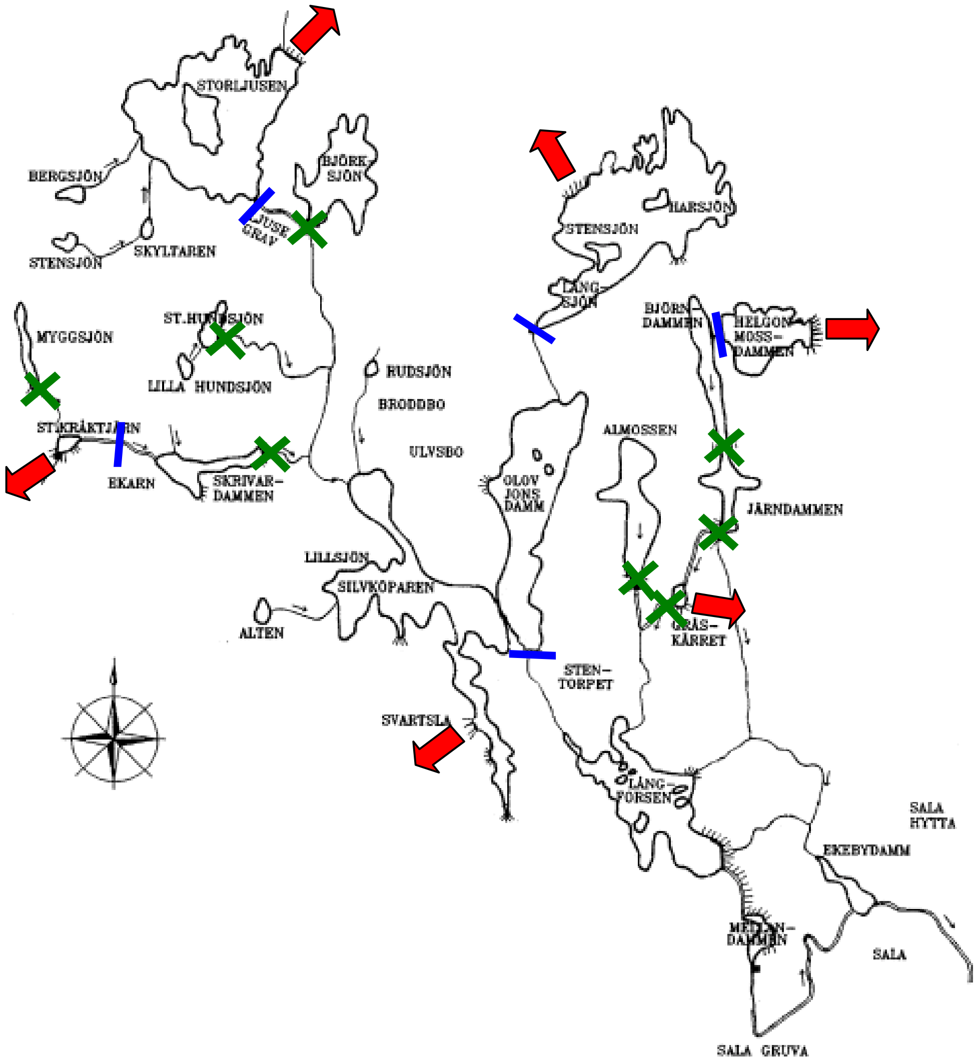
Table 4.1 shows the resulting highest water levels when the model is run with existing conditions. The water levels in table 4.1 do not include wave run up and water level inclination. Table 4.2 shows the required flood diversions in order to avoid overtopping of dam crests after implementation of measures proposed by the municipality of Sala for reduction of the hydrological load on the dams. The proposed measures are shown in figure 4.2. Running the model with existing conditions with a 30-year rain results in overtopping at Silvköparen and Harsjöarna. If the regulation is optimized meaning in practice that duration and frequency of the rain were known in advance, it is possible to handle a 30-year rain without overtopping of the dam crests.

A 100-year rain results in overtopping of Silvköparen and Harsjöarna whereas the water level in Långforsen just reaches the dam crest.

A design class I flood results in overtopping of Storljusen, Harsjöarna, Silvköparen, Olov Jons and Långforsen. In Olov Jons the water level reaches about 0.6 m above the dam crest whereas the water level in Långforsen reaches about 1.4 m above the dam crest.

The main part of the inflow to Långforsen is produced in the western part of the watershed whereas the water from Storljusen, Harsjöarna and Helgonmossen does not have any significant impact on the design class I flow.

According to the municipality of Sala about 24 millions m^3 of water is transported out of the system during a normal year. During the year 2000 when high floods occurred both in July and November the corresponding figure was 38 millions m^3. In order to avoid overtopping of the dam crests during a design class I flood almost as much water as during the whole year of 2000 must be transported out of the system during a month.



Diversion of flood to less sensitive areas

Reduction of discharge to about 0.1 m^3/s

Optimal reduction of discharge

Figure 4.2 ***Measures proposed by the municipality of Sala for decreasing the hydrological load on the dams***

Table 4.1 ***Resulting highest water levels with existing conditions and assumed contained overtopping. "Silvk + Olov J" refers to conditions if Silvköparen and Olov Jons are modelled as one reservoir.***

RESERVOIR	DAM-CREST	CLASS I RAIN	100-YEAR RAIN	30-YEAR RAIN	10-YEAR RAIN	5-YEAR RAIN
Storljusen	+92.10	+92.89	+92.05	+91.98	+91.91	+91.86
Harsjöarna	+81.50	+83.55	+81.78	+81.64	+81.51	+81.44
Silvköparen	+72.30	+76.71	+73.18	+72.86	+72.55	+72.33
Olov Jons	+72.60	+73.32	+72.27	+72.19	+72.10	+72.07
Silvk + Olov J	-	+75.61	+72.84	+72.60	+72.41	+72.29
Långforsen	+65.80	+67.23	+65.79	+65.76	+65.63	+65.54

Table 4.2 ***Required flood diversions in order to avoid overtopping of dam crests (after implementation of planned flood mitigation measures). "Total" refers to total volume of diverted water during one month.***

FLOOD-DIVERSION AT:	CLASS I RAIN		100-YEAR RAIN		30-YEAR RAIN	
	max (m^3/s)	total (1000 m^3)	max (m^3/s)	total (1000 m^3)	max (m^3/s)	total (1000 m^3)
Storljusen	5.3	3 931	0.8	1 184	0.4	733
St. Kråktjärn	4.2	1 467	1.7	629	1.4	564
Harsjöarna	4.1	3 105	0.9	1 218	0.6	961
Helgonmossen	1.6	1 184	0.6	829	0.5	682
Gräskärret	1.6	1 701	0.6	910	0.5	800
Svassla	33.1	9 086	5.0	1 588	-	-
Långforsen	4.3	1 573	-	-	-	-

4.4 Dam safety evaluation in Sala

4.4.1 Potential risk sources

A. Extreme floods - An extreme flood may lead to overtopping of the dam crests and a resulting dam failure. Overtopping of the dams is highly probable to cause a dam failure.

B. Leakage through the dams - Ongoing leakage through the dams may lead to internal erosion and finally to dam failure.

C. Trees growing on the dam crest – Uprooting may lead to extensive damage and leakage through the dam, which in turn may result in dam failure. Most of the trees are already cut down, but the remaining roots still constitute a risk source. Along the roots leakage can develop through macro-pore flow leading to piping. Roots that stop growing can lead to development of cavities in the dam. According to Hoskins and Rice (Hoskins et al. 1992) trees growing on embankment dams may in some cases have a positive effect on dam safety by improving the slope stability and an example is given of a 200 year old dam where the instability increased after all the trees were removed.

D. Floating debris - The spillways may be blocked by debris preventing full discharge. During an extreme flood it is probable that debris is produced since there is a lot of trees in the area. The risk of floating mires should also be considered. Since the dam gates in Sala are small it is not likely that the debris will pass through freely.

E. Gates are not opened – which can be caused by:

- Lack of observation – Water level observations in the reservoirs are done manually. During autumn and spring the dams are inspected on a daily basis, while in summer the dams are inspected once a month except during heavy precipitation when they are visited more often. Since there is no automatic measuring of water levels it is possible to miss some high floods. And even if the high floods are observed they may not be observed in due time to open the discharge facilities, warn the Rescue Service and evacuate the public.
- Gates getting stuck - The discharge facilities are regulated manually on a need basis. It is possible that the gates are left unregulated for long periods which may result in these gates getting stuck and being very difficult or even impossible to open when necessary. Floating debris can be another reason for the gates being very difficult to open.
- Non-trafficable roads - High floods and the need for emergency actions often coincide with bad weather situations like strong wind, snow and high precipitation. A bad weather situation may make it impossible to reach the discharge facilities and dams. Some of the dams in Sala are very difficult to reach due to bad or non-existent roads.

F. Human factor - The observations of water level and the operation of the discharge facilities are done manually which makes the dam safety of Sala highly dependent on the human factor. The fact that the entire water system is operated manually can lead to resource problems during a flooding situation.

A dam failure caused by uprooting trees or internal erosion can happen very suddenly whereas a dam failure due to overtopping is likely to be preceded by a period of much rain or snowmelt. Consequently the time for warning and evacuation is probably larger for a dam failure caused by extreme floods. On the other hand an extreme flood will likely cause problems at several places in the area and its surroundings at the same time meaning that available resources for rescue and safety has to be divided. An extreme flood is also likely to cause secondary effects like broken transmission lines and broken access roads making emergency actions more difficult.

A fault tree with top event “Dam failure” has been constructed for the dams in Sala.

Event trees have been constructed for the risks posed by high/extreme floods, leakage through the dam, trees growing on the dam crest and debris in the watercourse.

Since this thesis deals specifically with hydrological dam safety the only scenario that has been further analysed is the one with high/extreme floods leading to dam failure.

The existence of other risks however show that even if the water system is rebuilt to safely pass the design flood for instance by implementing flood diversions, refurbishment and upgrading of the dams cannot be excluded.

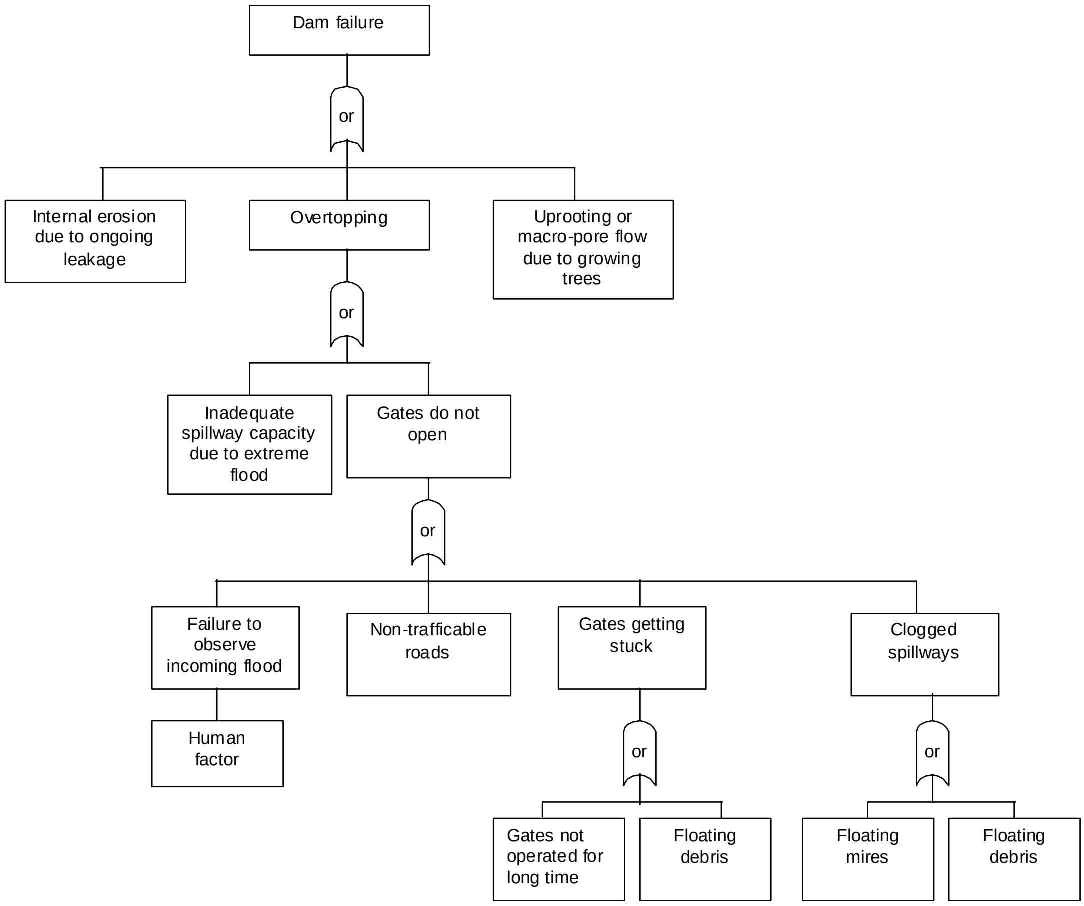


Figure 4.3 ***Fault tree with top event “Dam failure” for the dams in Sala***

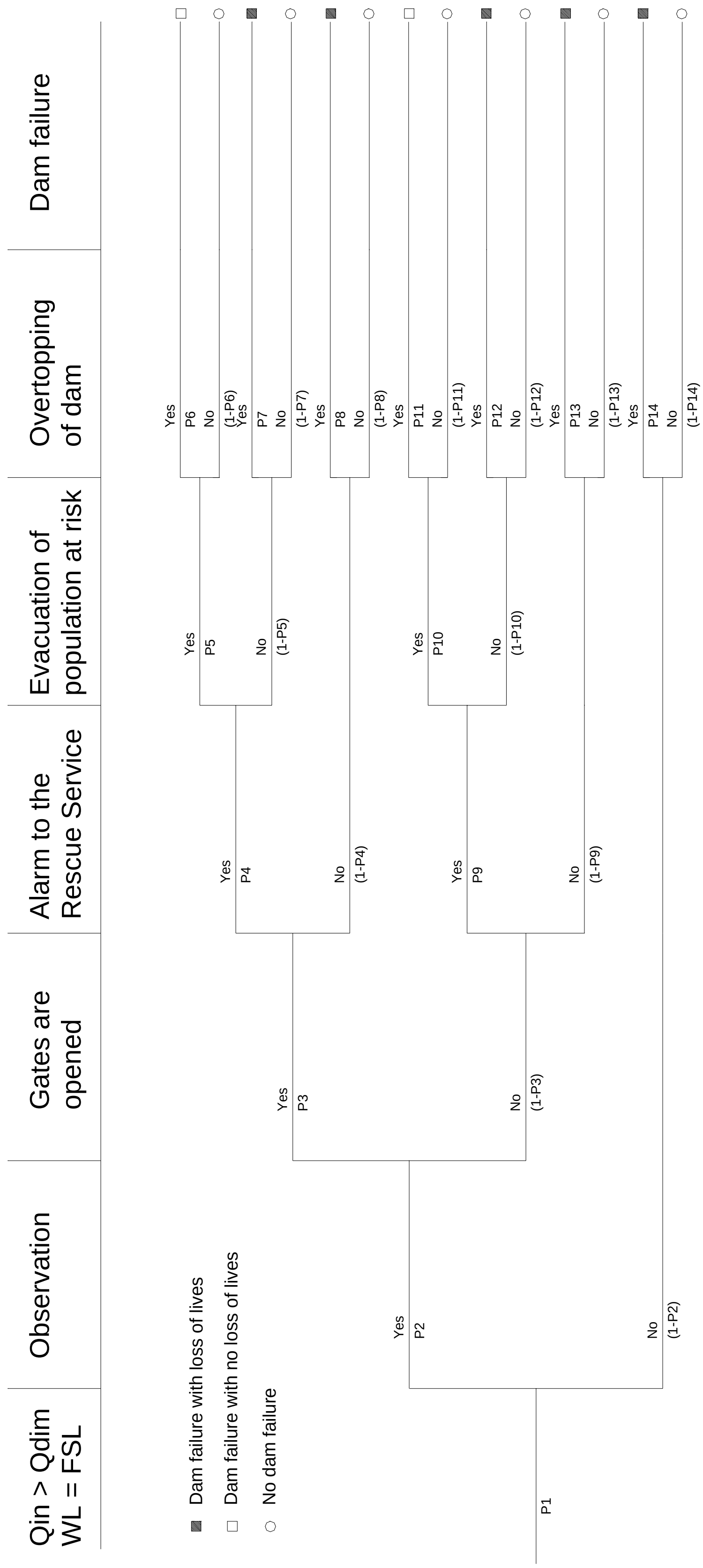


Figure 4.4 ***Event tree for initiating event $Q_{in} > Q_{dim}$ (FSL=Full supply level)***

4.4.1.1 The significance of the different events

Probabilities have been assigned to the single events in the event tree in figure 4.4 with initiating event Q_{in} = 100-year flood. The assessed probabilities for the events "observation of flood in due time", "gates are opened" and "alarm to Rescue Service" have then been changed one at a time. The purpose has been to evaluate how a change in the probability of a single event affects the probability of the final event – dam failure with loss of life as a consequence. The probabilities in table 4.3 are subjective probabilities or "best guesses" based on engineering judgement and should be used only in the context of evaluating the significance of the different single events and not for estimating the probability of dam failure in Sala. As can be seen in table 4.3 a change in the probabilities of the flood being observed in due time or the Rescue Service being alarmed affects the probability of dam failure with loss of lives more than a change in the probability of gates being opened.

Since the maximum discharge capacity only constitutes about 10 % of the risk class I flood, the operability of the gates is important but not crucial during an extreme flood. The time difference before dam crest is reached (initial water level = normal water level) if gates are fully opened compared to if they are closed is only about 1 hour for Olov Jons and 30 minutes for Långforsen.

A rise of the dam crest of Långforsen by 15 cm according to proposal from the municipality in Sala, increases the time from normal water level to overtopping by approximately 2 hours for Långforsen during maximum discharge.

More important than being able to open the gates are to observe a rise in water level at an early stage and to have a well functioning warning- and evacuation system.

Table 4.3 ***Assessed probabilities for the event tree in figure 4.4 with initiating event Q_{in} = 100-year flood***

EVENT	EVENT DESCRIPTION	ASSESSED PROBABILITY 1, AP1	AP2	AP3	AP4
1	100-year flood	$P_1=0.01$	0.01	0.01	0.01
2	Observation of flood in due time	$P_2=$*0.9*	0.9	*0.5*	0.9
3	Gates are opened	$P_3=$*0.9*	*0.5*	0.9	0.9
4	Alarm to Rescue Service	$P_4=P_9=$*0.9*	0.9	0.9	*0.5*
5	Evacuation of downstream population	$P_5=P_{10}=0.5$	0.5	0.5	0.5
6	Overtopping with open gates	$P_6=P_7=P_8=0.9$	0.9	0.9	0.9
7	Overtopping with gates closed	$P_{11}=P_{12}=P_{13}=P_{14}=0.99$	0.99	0.99	0.99
A	Dam failure	$P_A=P_1•P_2•P_3•P_4•P_5•P_6+ P_1•P_2•(1-P_3)•P_9•P_{10}•P_{11}=$ 0.0092	0.0095	0.0095	0.0092
B	Dam failure with loss of lives	$P_B=P_1•P_2•P_3•P_4•(1-P_5)•P_7+ P_1•P_2•P_3•(1-P_4)•P_8+ P_1•P_2•(1-P_3)•P_9•(1-P_{10})•P_{12}+ P_1•P_2•(1-P_3)•(1-P_9)•P_{13}+ P_1•(1-P_2)=$ **0.0055**	**0.0057**	**0.0074**	**0.0071**

4.4.2 Consequences of dam failure

The consequences of a dam failure of the dams of Olov Jons and Långforsen have been estimated. It should be pointed out that this is only a rough estimation. If Olov Jons dam fails several millions m^3 of water will be released. The total water volume of Silvköparen and Olov Jons dam at full supply level is 6 millions m^3. The flood wave will hit the summer houses just downstream of the dam and then continue down towards Långforsen and the national highway. The water volume at full supply level in Långforsen is 1.85 millions m^3. At a dam failure caused by an extreme flood both Olov Jons dam and Långforsen will most certainly collapse, in other words several millions m^3 of water will flow down and cause flooding in the city of Sala. Even if only Långforsen should break, 1 to 2 millions m^3 of water will flow down to the city of Sala. The houses downstream Långforsen will be hit by the flood wave which will then continue towards the city of Sala situated only about 3 km downstream of Långforsen.

Loss of human lives and injuries - The summer houses situated directly downstream Olov Jons dam will be hit by the flood wave following a dam failure and approximately 10 to 20 lives are in danger here according to the Rescue Service in Sala. If the dam at Långforsen should fail approximately 10 lives would be at risk since there are summer houses and a few permanent houses situated just downstream of the dam. The Rescue Service does not however estimate that a dam failure would lead to loss of lives in the city-centre of Sala. There is a possibility that a part of the water will flow south along the national highway. The road is heavily loaded with traffic during the winter sports holiday and if a dam failure should occur during that time there is a possibility of traffic accidents with loss of lives and/or injuries.

Environmental damages - The dams in Sala have a major value as recreational area and as historical monuments and a dam failure would lead to the destruction of an important piece of the industrial history of Sweden.

Economic damages – There will be no economic losses due to lost power production in the Sala case. Neither are there any large industries in the area that can be damaged by a dam failure. The summer houses and permanent houses situated immediately downstream of the dams are likely to be flushed away and damage on the national highway is probable. The Rescue Service estimates that the damages in the city will be in the order of hundreds of million SEK.

Bad publicity – The risk of bad publicity is probably not crucial in this case since the dam owner is a municipality. However a dam failure can cause the public to loose confidence in the local politicians of Sala.

4.4.2.1 Dam break analysis

For Långforsen with an assumed dam breach height of 2 m the approximate dam break calculations gives a peak flood during dam failure in the range of 900 m^3/s. For Olov Jons the same assumption concerning dam breach height gives a flood peak due to dam failure in the range of 1000 m^3/s. The time before the flood wave caused by a dam break of Långforsen reaches the city of Sala varies between 60 and 90 minutes. The time before the flood wave caused by a dam break of Olov Jons reaches Långforsen is only about 10 minutes. In other words the time for evacuation after dam failure has happened is very short.

The dam break calculations clearly indicate that a dam failure of Olov Jons dam or Långforsen would cause serious damages in the city of Sala and that the risk of human lives cannot be dismissed.

4.4.3 Probability of dam failure

The probability of dam failure in Sala cannot be given as an absolute value due to the many uncertainties both considering the status of the dams and the loads on the dams. The results from the hydrological modelling indicate that the probability of dam failure one particular year, due to hydrological load could be as high as 1 in 100. The accumulated probability of dam failure due to hydrological load during a 100-year period would then amount to 63 %.

4.4.4 Tolerable risk level

An absolute value of tolerable risk is impossible to give. What could be said concerning hydrological risks is that the requirement that Olov Jons and Långforsen should be able to safely handle a class I design flood is in line with present risk acceptance criteria abroad and that the risks posed by the dams today is intolerable.

4.4.5 Applicability of the Swedish design flood guidelines in the Sala case

Nothing has been found that indicates that the Swedish guidelines for design flood determination should be unsuitable in the Sala case due to the special features considering the historical value and age of the dams and the small scale of the water system. The design flood requirements of the dams of Olov Jons and Långforsen according to the Swedish design flood guidelines seem to be in line with international praxis.

4.4.6 Risk reduction alternatives

Since the dams in Sala are classified as historical monuments, alternatives for major reconstructions are restricted and it is not possible to solve the dam safety issue simply by reconstruction of the dams. Instead other measures such as flood mitigation and flood diversion are considered as possible means of decreasing the hydrological load on the dams. The municipality of Sala has suggested flood reduction measures including flood mitigation, flood diversion and dam crest rise, see figure 4.2 on page 21.

4.4.6.1 Flood diversion

According to the hydrological modelling of the system the runoff from the areas in the northeast part, that is, around Harsjöarna and Helgonmossen does not contribute significantly to the design flood. Neither does the runoff from the area around Storljusen. It is therefore questionable if the indicated flood diversions in figure 4.2 from Storljusen, Harsjöarna, Helgonmossen and Gräskärret will have any significant impact on the dam safety.

According to the hydrological model run about 9 millions m^3 of water needs to be diverted at Svartsla during one month during a class I design flood in order to avoid overtopping of the dam crests. And during a 100-year rain about 1,5 millions m^3 needs to be diverted.

Possible risks with implementation of flood diversion:

- Flooding of the areas at Storljusen, St. Kråktjärn, Harsjöarna, Helgon-mossdammen, Gräskärret and Svartsla may lead to economical and environmental damages
- Construction measures at the dams may affect their value as historical monuments
- Construction measures at the dams may disturb them in a way that influence dam safety negatively. Lack of documentation increases the difficulty to predict the behaviour of the dams
- Implementation of flood diversions might complicate the water system and its regulation with an increased need for supervision

The areas to be flooded consist mainly of forests and mires. Consequently the economical and environmental damages to be expected is not very extensive. There are though some farms situated about 1 km downstream the planned outlet at Svartsla. And about 1,5 km downstream Helgonmossdammen there are also some farms to be considered. Besides there are in total about 15 to 20 summer houses in the areas considered for flood diversion.

In order to keep necessary supervision and dependency on the human factor at a minimum the flood diversion should preferably be designed as a self-regulated system. It could consist of fuse plugs designed to be activated when a certain water level in the reservoir is exceeded or of ungated overflow spillways. The design however depends on the purpose of the flood diversion. Should diversion only occur during extreme floods or should also more modest flows like a 30 - or 100 year flood be partly diverted? If diversion is considered necessary only during extreme floods the overflows could be designed as fuse plugs or ungated spillways. However if more modest and more frequently recurring floods should be diverted as well it may be desirable that the fuse plugs/ungated spillways are complemented with regulated discharge facilities. Consideration should also be taken to the historical value of the dams when designing the flood diversions.

4.4.6.2 Rise of dam crest

The Public building administration of Sala has suggested a 15 cm rise of the dam crest at Långforsen to level +65,95. The time before overtopping occurs is then increased by approximately 2 hours during the design flood.

The results from the hydrological modelling indicate that if a dam crest rise is used as the only risk reduction measure the design flood requires a dam crest rise of almost 2,5 m of Långforsen if the wind effect is also considered. If Olov Jons and Silvköparen are considered as one reservoir a dam crest rise of almost 4 m including wind effects would be necessary at Olov Jons.

4.4.6.3 Warning system, emergency preparedness plan and evacuation plan

A warning system and an evacuation plan are necessary since no absolute guarantee against dam failure can be given. An emergency preparedness plan should be developed and the population living downstream of the dam should be informed that during certain circumstances their lives can be in danger, even if dam safety measures are implemented. When a dam failure is a fact, warning- and evacuation systems will be of limited use since the dams in Sala are situated so close to downstream buildings. Consequently warning and evacuation must take place before the dam failure is a fact, for instance for a significant leakage through the dam or for a significant water level increase in the reservoir. Here it is crucial that the right parameters are chosen for supervision.

4.4.6.4 Relocation of summer houses

If it turns out to be practically and economically unjustified to upgrade the dams to safely pass a class I design flood, an alternative might be to move the summer houses situated downstream Olov Jons dam and Långforsen in order to reduce the risk of lives being lost in case of dam failure.

4.4.6.5. Increased spillway capacity

If the existing emergency spillway is fully used at Olov Jons the discharge capacity is raised from 4.5 to 6.3 m^3/s. The time before overtopping during a class I flood is then increased by about 30 minutes. Besides, this flow will cause flooding of summer houses situated downstream. If the discharge capacity of Olov Jons is doubled from 4.5 to 9 m^3/s the time to overtopping is increased by about 1 hour.

A doubled discharge capacity of Långforsen from 4.5 to 9 m^3/s increases the time to overtopping by about 45 minutes.

4.4.6.6 Flood mitigation

The Public building administration of Sala has suggested that levees previously removed should be restored and new discharge facilities constructed at the smaller lakes/wetlands like Myggsjön and Almossen, to enable mitigation in the watershed. However, implementation of flood mitigation does not seem to have any significant mitigating effect on the extreme floods according to the results from the hydrological modelling.

4.4.7 Suggestion for risk management

Neither increasing the spillway capacity nor implementing flood mitigation measures in the watershed seem to have any significant effect on the dam safety in Sala. In order to safely handle the design flood and avoid dam failure due to overtopping it is necessary to divert the flood from the system.

Proposed risk management strategy for hydrological risks:

1. Construction of overflows at Svartsla and St. Kråktjärn
2. Installation of automatic water level measuring systems with alarm in Olov Jons dam and Långforsen
3. Rise of the dam crests of Silvköparen, Olov Jons and Långforsen

Though the focus in this study has been on the hydrological risks some obvious measures for reduction of other dam safety risks are also proposed:

- Regular dam inspections every third to fifth year and implementation of comprehensive dam safety evaluations
- Construction of a manual for operation, maintenance and supervision
- Construction of an emergency preparedness plan, an evacuation plan and information to the public
- Inspection of growing vegetation on the dams and removal of trees considered to pose a risk to the dam safety

5 Conclusions

5.1 Measures for reduction of the hydrological loads on a dam

One of the major risks posed on dams is the hydrological load. Statistics show that 1/3 of all dam failures were caused by overtopping. The hydrological load on a dam can be reduced by;

- increasing the spillway capacity,
- rising the dam crest,
- diverting the flood to less sensitive areas,
- implementing local flood mitigation measures in the watershed or
- changing the reservoir regulation strategies.

The use of local flood mitigation in situations where the total runoff volume during a flood is large is probably not a realistic alternative. The positive effect of local flood mitigation is probably highest for short and intense rainfalls and for watersheds with an initially fast runoff response. A literature study of the hydrology of mires indicates that mires are probably not particularly well suited for flood mitigation.

In a flooding situation the main objective must be to secure the safety of the dams since a dam failure could lead to catastrophic consequences. However, as far as possible one should strive for an integrated flood management where all aspects are considered, like risk of upstream- and downstream flooding, risk of dam failure etcetera, trying to find the best solution from a total point of view. All affected parties should be informed and offered to participate in the decisions on flood management strategy. It is essential that the different alternatives are thoroughly evaluated in order to avoid unpleasant surprises during a flooding situation.

5.2 Design flood

A comparison of international praxis shows that there is no common principle for design flood determination. There seems to be a certain tendency towards implementing risk analysis for evaluation of hydrological safety. Australia is however the only country that at present has fully integrated risk assessment in their design flood guidelines.

From a total dam safety perspective it can be questioned whether it is optimal to upgrade all class I dams to safely handle the design flood according to the Swedish guidelines for design flood determination. It is likely that in some cases those resources could be used on other dam safety measures that more efficiently should decrease the risk of dam failure. And since the risk classification system is coarse and does not include the probability of dam failure the application of the guidelines leads to a large variation in the residual hydrological risk posed by the dams. The ideal would be if the hydrological dam safety instead of being looked at separately is integrated with the overall dam safety and that the uniqueness of each dam and its environment could be fully integrated in the dam safety evaluation. A complete application of risk management in this way is probably not possible in practice – at least not in the nearest future. Deterministic guidelines are probably necessary at least as a complement to risk management in order to guarantee a fairly uniform minimum national level of dam safety.

In order to make it possible to take greater consideration to the individual features of the single dam and make it possible to take into account non-structural risk reduction measures the long-term objective in Sweden should be to complement the guidelines for design flood determination with a possibility to use risk assessment for evaluation of the hydrological dam safety. For the dam owner a risk assessment would help in allocating resources for dam safety improvements. In this respect more research in the field of assigning probabilities to extreme hydrological events would be desirable.

5.3 Dam safety evaluation in Sala

The dams in Sala are exposed to different potential risk sources of which floods are one. During a flooding situation in Sala the possibility to observe a rise in water level at an early stage seems more crucial for the dam safety than the reliability of the discharge facilities.

Hydrological modelling of the water system

A 30-year rain seems to be about the upper limit of what the water system can safely handle at present. A design class I flood results in overtopping of Storljusen, Harsjöarna, Silvköparen, Olov Jons and Långforsen. In Olov Jons the water level reaches about 0.6 m above the dam crest whereas the water level in Långforsen reaches about 1.4 m above the dam crest during a class I flood.

Consequences and probability of a dam failure

In case of dam failure of Olov Jons or Långforsen about 10 to 30 lives would be at risk and the economical damages would probably amount to hundreds of million SEK. Besides, an important monument of the Swedish industrial history would be seriously damaged.

The probability of dam failure in Sala cannot be given as an absolute value but the results from the hydrological modelling indicate that the probability of dam failure one particular year, due to hydrological load could be as high as 1 in 100.

Tolerable risk level

What could be said concerning hydrological risks is that the requirement that Olov Jons and Långforsen should be able to safely handle a class I design flood is in line with present risk acceptance criteria abroad and that the risk posed by the dams today is intolerable. In Sala the determination of tolerable risk has to be a political decision.

Applicability of the Swedish design flood guidelines

Nothing has been found that indicates that the Swedish guidelines for design flood determination should not be suitable in the Sala case due to the special features considering the historical value and age of the dams and the small scale of the water system.

Risk reduction

Neither increasing the spillway capacity nor implementing flood mitigation measures in the watershed seem to have any significant effect on the dam safety in Sala. In order to safely handle the design flood and avoid dam failure due to overtopping it is necessary to divert the flood from the system.

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HYDROLOGICAL DAM SAFETY

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SUMMARY

International statistics show that 1/3 of all embankment dam failures were caused by overtopping which in turn depends on the hydrological load on the dam.

In this study the different factors affecting the hydrological load on a dam is described together with different ways of decreasing the load in order to obtain a higher dam safety. Advantages and disadvantages with different strategies for flood handling is discussed together with the importance of striving towards integrated flood management where concern is taken to dam safety as well as flooding problems.

Strongly connected to hydrological dam safety is the design flood and different methods for design flood determination are described with special attention to the possibilities to use risk analysis. The Swedish guidelines for design flood determination are described and a comparison is made with international praxis showing that there is no common principle used for design flood determination. Some countries are using deterministically determined floods like PMF, Probable Maximum Flood, whereas others are using probabilistically determined floods like the 10,000 years flood.

Different aspects of the Swedish guidelines for design flood determination are discussed, like risk classification, choice of precipitation sequence, small versus large dams and regulation strategies. A short discussion is also held over the possible effects of a potential climate change.

1 INTRODUCTION

Together with internal erosion, overtopping is the most common cause of dam failure for embankment dams. Overtopping is connected to the hydrological load of the dam, directly through an extreme flood or indirectly by malfunction of the discharge facilities during for instance a high flood. This means that the hydrological and hydraulic situations will always be interlinked in an overall assessment of the safe performance of a dam.

In order to decrease the risk of overtopping either the functional capacity of the dam can be changed like increased discharge capacity or the basic conditions affecting the hydrological load can be changed. One way of decreasing the hydrological load is to implement flood mitigation measures in the watershed. The effects, environmental as well as safety and economical, must however be evaluated in order to see if something is really gained by the measure.

Connected to the hydrological load of the dam is the concept of design flood. What extreme flows should the dams be able to accommodate? In this thesis different principles for selecting spillway design flood are considered and the Swedish guidelines for assessing design flood is compared with design flood as applied internationally.

The intention with this paper has been:

- To analyse the hydrological loads affecting a dam, what causes the loads and how to handle them in order to reduce the load on the dam. Special attention has been given to the advantages and disadvantages of implementing local flood mitigation in the watershed
- To elaborate on the different methods for spillway design flood determination with special attention to the use of risk analysis
- To analyse the Swedish guidelines for design flood determination and compare with international praxis for design flood determination

2 DAM SAFETY IN SWEDEN

2.1 Short history

During the autumn of 1985 parts of Sweden experienced extensive flooding resulting in the failure of the 21 m high Noppikoski dam and some minor dams as well which lead to demands for improved dam safety. In 1990 the Flood committee presented the report "Riktlinjer för bestämning av dimensionerande flöden för damm-anläggningar" (Guidelines for design flood determination for dams) and in 1997 the power industry published RIDAS (the power companies guidelines for dam safety). This policy document was revised in 2002 (Svensk Energi 2002). A dam safety authority was established in 1998.

2.2 Dam safety requirements

According to the Swedish Environmental Code (Miljöbalken, Chapter 11, 17§) owners of water structures shall maintain them in such a way as to prevent damage being caused to public or private interests by changes in water conditions. It is also stated (Miljöbalken, Chapter 11, 18§) that the ones responsible for maintaining a dam for water regulation are liable for damage caused by the failure of the dam to give the intended protection against escaping water (dam break). This shall apply even when the damage is not caused by the person responsible for maintenance or by a person for whom the former is responsible.

Dam safety requirements in Sweden are guidelines and not regulations. The Swedish power industry has agreed to follow the Swedish guidelines for establishing the hydrological design flood (Flödeskommittén 1990) and RIDAS, Guidelines for dam safety of the power industry in Sweden (Svensk

Energi 2002). According to RIDAS dams shall be designed to withstand every possible load they can normally be expected to be exposed to during their lifetime. Dams belonging to risk and consequence classes in the highest rank shall in addition have the ability to withstand unlikely but possible events that can arise, without failure. Damages however can be accepted.

2.3 Dam failure

International statistics show that the failure rate of modern dams is of the order of $2 \cdot 10^{-4}$ as the mean probability of failure for a given year. According to (Fahlbusch 1999) the total number of fatalities due to dam failure over a 200 year period is 11 000 people.

In Sweden only one high hydropowerdam has failed. It was the Noppikoski dam, a 21 m high embankment dam that failed in 1985 due to overtopping. The dam failure did not result in any fatalities but the economic consequences were estimated to nearly 200 million SEK. The only fatality due to dam failure happened in 1973 when a dam at Sysslebäck failed. One person died. In 2000 a 20 m high tailings dam at Aitik failed, releasing about 2 millions m^3 of water. No person was injured due to the failure.

The most common causes of failure of embankment dams according to international statistics (ICOLD 1995) are:

- Overtopping 32%
- Internal erosion 27%

Of the dam failures caused by overtopping 73% are due to inadequate spillway capacity and 27% due to spillway gate failure (Berntsson 2001).

The causes of dam failure of concrete dams according to international statistics (ICOLD 1995) are:

- Problems in the foundation 64%
- Overtopping 21%

The statistics do not include dams of height less than 15 m unless the water volume of the reservoir exceeds 1 million m^3.

A dam failure is linked with negative consequences that may be difficult to estimate in advance. Possible consequences of a dam failure are:

- Loss of human lives and injuries
- Environmental damages
- Economical damages – Damages on infrastructure and lost power production incomes
- Bad publicity – After the flooding in Sweden in July 2000 the public criticised the power industry for not taking their responsibility. It is not difficult to imagine the criticism that would follow a major dam failure

3 HYDROLOGICAL LOADS AFFECTING THE DAM

A dam is exposed to different weather loads during its lifetime. The main weather loads affecting the dam are wind, ice and hydrological load caused by precipitation or snowmelt. This thesis only deals with hydrological loads. It could however be interesting to analyse existing weather data in order to estimate the probability that different weather loads coincide in time like wind and high floods or high floods and ice.

With hydrological loads are here meant loads induced by floods. A distinction can be made between extreme floods, high floods and normal floods depending on their magnitude. In this study extreme floods refer to floods that exceed the design flood according to the Swedish guidelines. High floods are defined as in the report *Flood attenuation in regulated Swedish river systems* (Rytters et al. 1995) that is, floods with a return period from 50 years up to the design flood. Normal floods refer to flood events of magnitudes smaller than high floods.

The hydrological load on the dam is determined by

- The magnitude of the flood
- The duration of the flood
- Precedent storm events
- The initial water level in the reservoir at the start of the flood
- The discharge capacity of the dam

Hydrological dam failures are failures caused by

- Overtopping
- Sliding or overturning due to increased water load
- Internal erosion due to an increased water pressure gradient

3.1 Overtopping

The sensitivity of overtopping is very much dependent on dam type. Concrete dams are much more likely to stand overtopping than embankment dams.

This is reflected in the design flood guidelines of some countries where a larger flood should be used for embankment dams than for concrete dams and the Swedish guidelines for design flood determination states *"Normally one might assume that concrete dams founded on rock, that can withstand overtopping can be classified as class II dams"*. Overtopping of embankment dams cause failure due to erosion whereas for concrete dams the failure due to overtopping is caused by decreased stability. Whether or not overtopping will lead to dam failure depends on the duration, depth, velocity and volume of water flowing over the crest and of the properties of the dam. Overtopping of an embankment dam is most often considered as equal to dam failure. However information exists that certain embankment dams can withstand some overtopping for instance (Lempérière 1997) states that *"many small homogenous dams of clay can support almost 0.5 m of overtopping over several hours"*.

Overtopping can have different causes and it is probably often a combination of different events that leads to the overtopping.

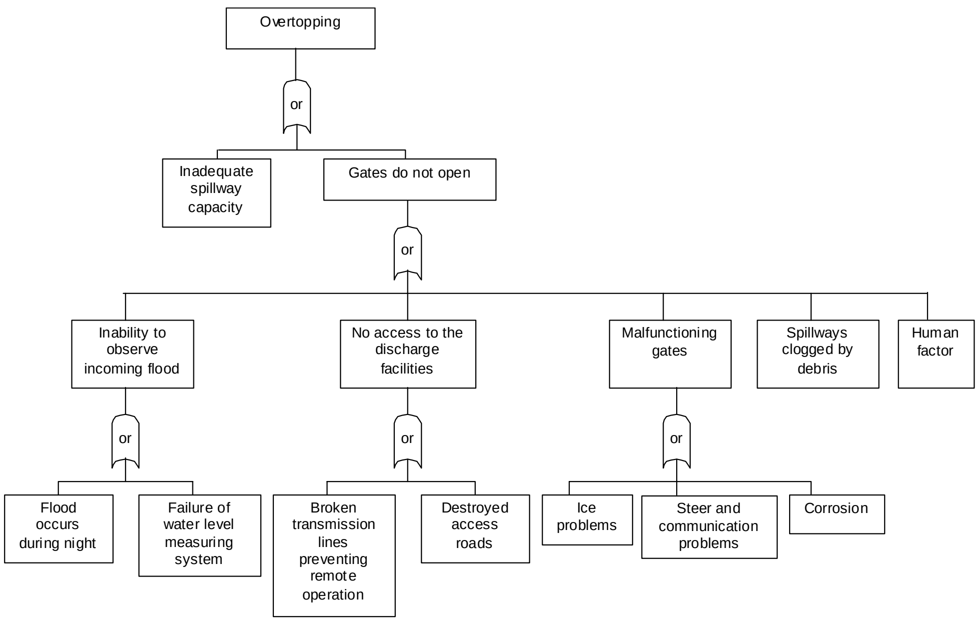

Figure 3.1 ***Fault tree for overtopping***

Inadequate spillway capacity

The major part of the spillways in existing Swedish dams were designed and constructed quite a long time ago and new knowledge on the magnitude of possible extreme floods have developed since then. The floods used for designing the spillways have been found to be too small (Flödeskommittén 1990) thus when the safety of existing dams is evaluated the spillway capacity is often found to be inadequate.

Inability to observe incoming flood

A failure of the water level measuring system can lead to an incoming flood not being observed in time. Inability to observe an incoming flood in time can also be a fact if the flood occurs during night or weekends. At high consequence dams however the water level measuring system is often connected to an alarm system giving a signal if the connection is broken.

No access to the discharge facilities

Broken transmission lines leading to the gates not being possible to remotely operate is a risk during a flood. It may also be difficult or even impossible to reach the dam due to damaged access roads making it difficult or impossible to manually operate the gates.

Malfunctioning gates

Malfunctioning gates can be due to different causes like problems with ice, problems with steer and communication equipment and corrosion of mechanical parts.

Spillways clogged by debris

During an extreme flood problems with debris may develop. Debris reaching the dam can lead to decreased discharge capacity by clogging the spillways and jammed debris can make the gates difficult or sometimes even impossible to open and close. Possible debris is trees, bridges and floating mires. The risk of debris is larger at small dams with small gates since with large gates it is more likely that the debris can pass through freely.

Human factor

During a flooding situation it is possible that the personnel responsible for the operation of the dam and discharge facilities act in an unpredicted way due to stress, fear and panic. Extreme floods are very rare and accordingly the operative personnel are unfamiliar with the situation. During high and extreme floods it is possible that several dams are affected, which may lead to resource problems among the operative personnel.

Other factors

Overtopping can also occur due to wind induced wave run up, settlement of the dam crest, earth- and rockslides or avalanches causing surge waves and failure of upstream dams.

3.2 Factors affecting the hydrological load

The hydrological situation in a river system is related to many factors such as climate, hydrological runoff characteristics of the catchment like topography, soil and vegetation features, land use and size and shape of the catchment, reservoir regulation strategies and spillway capacity. Consequently a change in one or more of these factors will affect the hydrological load on the dam.

3.2.1 Climate change

There is an ongoing discussion on a possible future climate change with a global warming scenario caused by the increased discharge of greenhouse gases. There is also a discussion on the impacts such a climate change may have on the runoff pattern, especially on the magnitude and frequency of extreme floods.

Climate change research is carried out around the world both on a global and on a regional scale. In Sweden regional climate simulations has been performed by

SWECLIM, Swedish Climate Modelling Programme.

During the last hundred years the average global temperature of the earth has increased by approximately 0.6 ºC (SWECLIM 1998). Climate simulations by SWECLIM (SWECLIM 2002) give scenarios of the climate in Sweden 100 years ahead using two different global climate models and two different emission scenarios for greenhouse gases. The scenarios give an increase in temperature between 2.5 and 4.5 ºC, with a higher temperature increase during winter than during summer. The precipitation scenarios show an increase in both mean precipitation and intensity. The increase is larger during winter than summer, with an increase in the northern part of Sweden during winter of 30-60% while the precipitation in southern Sweden during summer decreases. In the scenarios the higher precipitation will to some extent be evened out by a similar higher evaporation.

The annual report 1999 from SWECLIM (SWECLIM 1999) gives some preliminary results on how climate changes could possibly affect the Swedish water resources in the future. The winter period may be shorter, warmer and wetter reducing the snow storage. Accordingly the probability of the most extreme floods may in general decrease, mostly because of a reduction of the spring flood. However the probability of high summer and autumn floods may increase, particularly in the north. The report points out that the results are preliminary and should not be seen as forecasts. In SWECLIM´s annual report 2002 the spreading and uncertainties connected to the predictions on how a climate change would affect the runoff pattern are further emphasized.

According to a report on climate change impacts on runoff and hydropower production in the Nordic countries the flood risk in large, continental catchments is expected to be reduced, while the flood risk in small catchments can increase (Saelthun et al. 1998). Flood volumes for longer duration show less increase or more reduction than daily mean flood meaning that large reservoirs will be less vulnerable to climate change impacts than small reservoirs. The report also states that the effect of climate change upon the flood situation is less than the general uncertainty in estimating extreme floods.

During the last few years there has been some examples of high floods during autumn/winter caused by long lasting rains in combination with snowmelt due to mild weather. It is however too soon to say if they are within the variation of the existing climate or due to a change in the climate. For instance during February 2002 the southern parts of Sweden experienced a flooding situation. The flood was caused by long lasting rains, no vegetation to intercept water, saturated grounds, simultaneous snowmelt and full reservoirs. Taken together this leads to a fast runoff and a very fast response in increasing reservoir levels due to a rain since there is no damping capacity left in the system. A similar rain during summer would not have given as high floods.

3.2.2 Change of the hydrological properties of the watershed

The hydrological properties of the watershed can be affected by a land use change. Examples of land use changes are increased deforestation, drainage, cultivation and urbanisation. An analysis of the floods during summer and autumn of 2000 and winter 2001 states that a change in land use does not have any major influence on flows in larger areas (Svenska Kraftnät 2001).

3.2.3 Implementation of local flood mitigation measures in the watershed

To reduce the flood peaks the runoff can be attenuated over longer periods. This means primarily that more active storage volumes have to be created. In order to decrease the hydrological and hydraulic loads of the dam local attenuation of the runoff in the watershed like controlled inundation of flood plain areas, wetlands and forest areas can be implemented.

Active flood mitigation is sometimes used in the reservoirs but local mitigation of the flood in the watershed before reaching the reservoir is not often used as a dam safety measure. In urban hydrology local handling of storm water is used in order to reduce the load on sewer system and water treatment plants. At least in theory the same principle should be possible to use also as a dam safety measure. The objective of flood mitigation in the watershed is to reduce the flood peaks by attenuating the runoff over longer periods. In figure 3.2 the hydrograph A shows the runoff before flood mitigation and hydrograph B shows the runoff after implementation of flood mitigation measures.

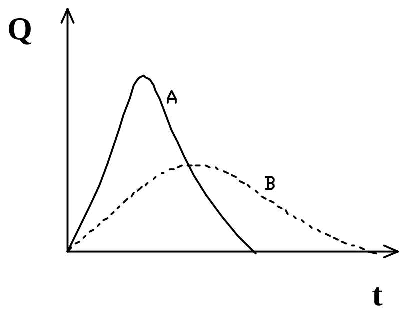

Figure 3.2 ***Runoff before (curve A) and after (curve B) implementing flood mitigation in the watershed***

The water balance in a watershed can be described as:

$$Q = p - e - i - \frac{dS}{dt}, \text{ where}$$

Q = flow

S = water storage in the watershed. The stored water can be in form of snow, water in natural lakes, rivers and man-made reservoirs, groundwater and water in the ground above the groundwater table.

p = precipitation intensity

e = evaporation rate

i= interception by vegetation

t = time

One objective of flood mitigation is to decrease Q. This can be achieved by increasing the amount of vegetation in the watershed in order to increase i. However during very large storms the effect of interception is probably negligible particularly during autumn and winter. A more efficient way to decrease Q is to increase S by creating more effective storage volume in the area. This can be achieved by:

- Controlled inundation of areas where the consequences of flooding are less severe like mires, fields and forests, by constructing levees and discharge facilities
- Restoration of wetlands. Besides fulfilling a primary purpose of flood mitigation these wetlands can also develop a value as recreational areas and for promoting ecological diversity
- Clearing of existing watercourses and lakes

The time of concentration is the time at which all of the watershed contributes to the runoff. By increasing the time of concentration the flow is attenuated over longer periods. This can lead to a decreased hydrological load on the dam and increased time for warning and evacuation of downstream areas. However the effect of superposition of the different flood components is important to consider. The strategy concerning the time of concentration should be to delay the different secondary flows and the main flow in such a way that they reach the dam at different times and at a less critical time.

The time of concentration can be increased by:

- Blocking of the drainage systems of fields or mires
- Restoration of the natural course of rivers that have been widened, straightened or made less permeable by for instance concrete lining

Below are listed some properties that are desirable for areas used for flood mitigation:

- Soils with high permeability and high porosity
- Vegetation with a high water absorption capacity
- Existence of natural embankments
- Existence of natural wetlands
- Possibility to construct discharge controlling facilities without too much efforts
- Small negative impacts of inundation
- Large non-developed areas

Benefits with flood mitigation in the watershed:

- The hydrological load is not only reduced for the dam but for the downstream area of the dam as well. It is a possible good example of integrated flood management leading both to increased dam safety and reduced flooding of downstream areas
- Water can be discharged from the watershed during dry periods
- It can be a rather cheap measure compared to rising dam crests, upgrading of existing spillways and construction of new spillways
- In case it might be impossible to make any structural measures on the dam in order to handle the safety
- The flooding can be diverted to a place where it makes the least damage

Disadvantages with flood mitigation in the watershed:

- Negative consequences on the inundated area. Manmade inundation of some areas such as wetlands and forests may have a negative impact on the fauna
- For a class I design flood situation it is very large volumes of water that need to be stored for significant mitigation of flood peaks
- If a high flood that has been damped and stored is succeeded by another high/extreme flood the entire stored water volume may have to be released leading to an increased load on downstream dams and increased flooding consequences
- The effect on dam safety depends on the different runoff times for the flood components reaching the reservoir. Flood mitigation in the watershed should delay the different flood components. However this can also lead to a higher hydrological load of the dam if the delayed flood components are not dispersed and therefore tend to reach the dam simultaneously at a more critical time
- Flood mitigation in the watershed can lead to negative economic consequences if the mitigation causes environmental damages and reduced water for power production
- Flood mitigation in the watershed implies increased need for supervision and control

If the total water volume to be discharged during a flood is large, local flood mitigation is probably not a realistic alternative since large areas for inundation would then also be needed. The positive effect of local flood mitigation is therefore probably highest for short and intense rainfalls and for watersheds that initially have a fast runoff response.

Implementation of flood mitigation requires a thorough analysis of the whole watershed. It is important to analyse the possible effects on safety, environment and economy using a systems approach. A flood mitigation strategy as a successful dam safety measure is highly dependent on reliable weather and flood forecasts (based on hydrological models) as well as reliable hydraulic models.

As a general dam safety strategy during floods it is in most cases probably wiser to release as much water as possible from the system instead of trying to store it in the watershed upstream. There should however be situations where local flood mitigation could be a suitable solution and there should be potential areas suitable for this measure in Sweden since we have many sparsely populated areas, especially in the north.

3.2.3.1 The use of mires for flood mitigation

The idea of using areas in the watershed for local flood mitigation during high/extreme floods to promote dam safety arose during a case study of hydrological dam safety. The case study was performed for a water system located in Sala, a city located in the central part of Sweden. In the area of Sala there is a high presence of mires. If these wetlands create additional retention capacity - absorbing water during floods and releasing water during dry periods they would be very well suited for local flood mitigation. In order to get more knowledge of the hydrology of wetlands a literature study was performed. Unfortunately the present knowledge is limited. It was discussed to perform a laboratory test of the hydraulic properties of some mire samples from Sala. However it was decided that such a laboratory test would be outside the scope of this study. It could though be an interesting future research project. A large area of Sweden is covered by different types of wetlands and from a dam safety point of view a survey of their hydrological and hydraulic properties could be useful. Below follows a summary of the information found in the literature.

Sweden is one of the countries in the world that has the highest portion of mires. About 10 million ha or more than 20 % of the area is mires (Larsson). Available literature is primarily related to research carried out during 1972 to 1976 at two mires in Sweden, Komosse in Småland (Brandesten 1987) and Solmyren in Lappland (Jansson 1981).

A mire can be divided into two layers. The upper layer called the acrotelm is thin, partly aerobic and biologically active while the lower layer called the catotelm is saturated, anaerobic and consists of dead material. It is mainly the acrotelm that will influence the hydrology of a mire. The groundwater level is always present in this layer and the runoff from a mire is consequently concentrated to the upper more permeable part of this layer. The acrotelm can be permeable as a coarse sand while the catotelm is more similar to a clay soil (Burt et al. 1990). The thickness of the acrotelm can vary between 7-8 cm to 60-70 cm depending on type of mire (Brandesten 1987).

The more dynamic runoff being concentrated to the upper layer means that this runoff is strongly dependent on the actual water level. During dry periods the groundwater level drops below the conductive surface layer and the runoff is reduced or non-existent. Field studies indicate that groundwater levels deeper than 10 cm below ground surface do not produce significant runoff from undisturbed mires (Brandesten 1987). Information also exists of a critical ground water level 5-6 cm below the surface of the mires (Burt et al. 1990). Below this level the groundwater fluctuations were found to be slow, the horizontal flow almost ceased and the runoff was strongly reduced.

The groundwater level is close to the ground surface during most of the year and the mires therefore practically always stay near face saturation. This means that small amounts of rain are sufficient to rise the water level to the surface or close to it. This in combination with the fact that the upper permeable part of the acrotelm is thin means that completely saturated areas producing surface runoff can expand very fast in mires

(Burt et a. 1990). Consequently the storage capacity is limited.

Evaporation plays an important roll in the runoff from mires. When the groundwater level has sunk below a critical level, any further lowering of the groundwater surface can be directly referred to evaporation losses. A survey of Solmyren in the inner of Norrland showed that the evaporation from the mire equalled the potential evaporation (Salwén 1987).

Consequently, it does not seem likely that mires are particularly well suited for flood mitigation. The groundwater level lies near the ground surface except during dry periods and the upper permeable layer is so thin that the storage capacity is limited and accordingly mires respond quickly to rain by producing surface runoff almost immediately. Instead of mitigating the flood peaks the mires probably increase them. There are however a variety of different types of mires and the damping capacity may differ from mire to mire. If the mires are thick and located in a depression in the landscape they can probably have a ponding effect and from a hydrological/hydraulic point of view be treated as lakes.

3.2.4 Diversion of floods

To reduce the hydrological load on the dam the flood can be diverted away from the watershed in order not to reach the dam. Either the entire water flow or a part of it can be diverted. The benefit with flood diversion is that the total hydrological load of the dam can be reduced. The disadvantage is that diverting the water to a course it normally does not take can lead to negative consequences along the new watercourse.

There is a principal difference between local flood mitigation and diversion in the sense that local mitigation leads to a dispersion of the flood in time whereas diversion leads to a displacement of the flood in space. In the case of diversion, the water never reaches the dam contrary to local mitigation where the water eventually will reach the dam.

3.2.5 Reservoir regulation strategies

During the floods in Sweden in July 2000 the power industry was criticized for not taking enough consideration to safety aspects in their reservoir regulation strategies. An analysis of the floods during summer and autumn of 2000 and winter of 2001 states that the flooding could probably not have been avoided even with changed regulation strategies (Svenska Kraftnät 2001). The safety of the dams also has to be prioritised before flood mitigation for downstream areas since a dam failure could lead to catastrophic consequences.

A change in the seasonal pattern of floods with a decreased spring flood and an increase in the summer and autumn floods and possibility for high floods even during winter is a possible scenario according to climate studies. Late summer/autumn is the time when the storage capacity of the reservoirs are utilised. A high flood together with a full reservoir could lead to a hydrological load as high as one caused by an extreme flood when the reservoir is below full supply level.

A Spanish study (Andrés 2000) concludes that by keeping a part of the storage volume for safety purposes it is possible to considerably increase the safety factors. Keeping a part of the storage volume for safety purposes could lead to a loss in production incomes for the dam owner but in comparison with the costs for upgrading the dam to safely pass the design flood it may however be an interesting alternative in some cases. At least for dams where a dam failure will not cause catastrophic consequences. In a report on flood mitigation possibilities at Swedish dams (Rytters et al. 1995) the possibilities of creating effective storage capacity for flood mitigation using pre-spilling in order to decrease the demands on discharge capacity are discussed. The report concludes that in reality the possibilities to effectively use pre-spilling are very limited.

A change in the regulation strategies with a lower full supply level during autumn and winter could have an effect on flooding due to short, intense rains. When it comes to long lasting rains that can last for several weeks the effect of changed regulation strategies are however more uncertain since then it is likely that the reservoirs will be full at some point irrespective of the initial water level.

It is difficult to predict floods in advance and there is no guarantee that a high flood will not be succeeded by an even higher flood. For the large regulated river basins the whole system of dams interact. A change in the regulation strategy of one dam might lead to negative consequences for downstream dams. Besides, the regulation is controlled by the conditions provided by the environmental court. Changing the reservoir regulation strategies is therefore a complex task that requires extensive analysis in order to evaluate its overall effect on dam safety. This should however not be a reason for not looking over the old water laws that are written for a seasonal pattern where high floods mainly occur due to spring snowmelt. Changing the conditions given by the environmental court are a complicated, time consuming and costly process but in a long-term perspective it is probably necessary in some cases.

In the future applying optimal, multipurpose regulation strategies may be a crucial issue for water resources management of river basins around the world. In Sweden however the large rivers are regulated for hydropower production and multipurpose regulation strategies in these existing systems is probably very difficult to apply in practise. It should be easier to apply when it comes to constructing new dams. Besides the benefits are probably larger in countries with other needs for water management than Sweden, for instance countries with a water shortage and more extreme and recurring floods.

3.2.6 The spillway capacity of the dam

Increasing the spillway capacity is a way of securing that the requirements according to the guidelines for design flood are fulfilled. Increased spillway capacity can be obtained by either enlarging existing spillways, open up existing spillways that have been closed like spillways used for timber floating, or by constructing new ones. One solution is to install auxiliary spillways in the form of self-regulating fuse plugs.

A larger spillway capacity can lead to increased negative downstream consequences like erosion, flooding and increased load on downstream dams. It is therefore important to take into consideration the whole river system and thoroughly analyse the possible effects of an increased spillway capacity at a certain dam. At some dams it might be disproportionately complicated and expensive to increase the discharge capacity due to technical causes.

3.2.7 Rise of the dam crest

A rise of the dam crest is another way of securing that the design flood requirements are fulfilled. There is however some risks connected to a dam crest rise and these risks should be evaluated before the rise is done.

Possible risks are:

- A higher water level results in a higher hydraulic load on the dam. It is therefore important to control that the dam is able to handle a higher hydraulic load, even if it is for a short period of time
- A higher flood than the one used for designing the elevated dam crest may occur. If such a flood should occur a rise of the dam crest would lead to the release of an even larger water volume in case of a dam failure
- A rise of the dam crest might lead to a false sense of security and other safety measures might be neglected

- When performing the rise of the dam there is a possibility of disturbance of the existing dam, which might lead to a decreased safety. And during the modification of the dam construction accidents might occur. Graham (Graham 2000) states that *"modifying a dam that already has a very small chance of failure may increase overall risk to human life"*. This has also relevance when reconstructing spillways in order to increase the spillway capacity

3.2.8 Integrated flood management

It is not always possible to fully control floods and no flood defence structure can be designed for absolute safety. Instead a flood mitigation strategy can be applied where the risk of flooding is reduced as far as possible with reasonable means. It must be made generally recognized that living downstream a dam or close to a river involves a risk - a risk that may be mitigated but not totally eliminated.

When regulating a hydropower dam there is a conflict of interests. Figure 3.3 illustrates in a simplified way different objectives of reservoir regulation.

The aim of the dam owner is to:

- Run the dam for optimized power production
- Keep the dam sufficiently safe at a cost as low as possible

The aim of society, the public and those living upstream and downstream is to:

- Keep the dam safe
- Reduce upstream and downstream flooding

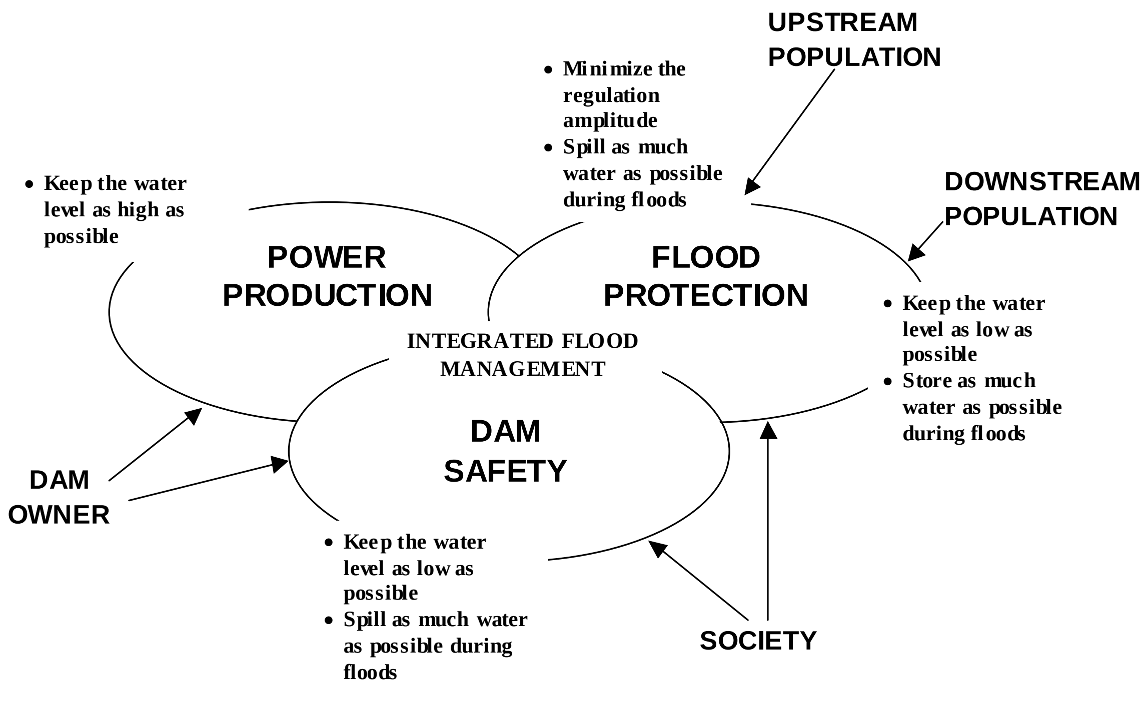

Figure 3.3 ***Different objectives of reservoir regulation***

Superior to both power production and flood protection is the safety of the dam. However other relevant factors than dam safety should as far as possible be considered when dealing with flood management.

An aspect of the importance of integrated flood management that should have become obvious in Sweden during the flooding in 2000-2002 is the need to integrate the risk of flooding and dam failure in the physical planning process. Before the regulation of our rivers everyone was well aware of the risk of flooding along the watercourse and learnt to live with these recurring floods. But because the hydropower dams as a side effect provide a certain protection against flooding a false sense of security has arose and we easily forget that high floods is a natural recurring phenomena that can not be fully controlled. New developments in flood prone areas should not be allowed. And in the case of existing buildings and infrastructure in flood prone areas, often consisting of summerhouses, a solution could be to move the houses. Compared to the costs for recurring flood damages and the costs for upgrading dams to safely handle a class I design flood it may turn out to be an economically sound solution. These flood prone areas could instead be converted to valuable recreational areas.

4 DESIGN FLOOD

Figure 4.1 shows the principles used for hydrological dam safety management in Sweden today whereas figure 4.2 shows how the hydrological safety could be handled with a risk approach.

The principle used today for managing the hydrological safety is based on evaluating the ability of the dams to safely handle a calculated extreme flood. The risk approach considers different floods in combination with other factors producing different flood scenarios. The risks posed by the different flood scenarios are estimated and evaluated to determine if they are acceptable or not. If they turn out to be unacceptable, risk reduction measures are implemented.

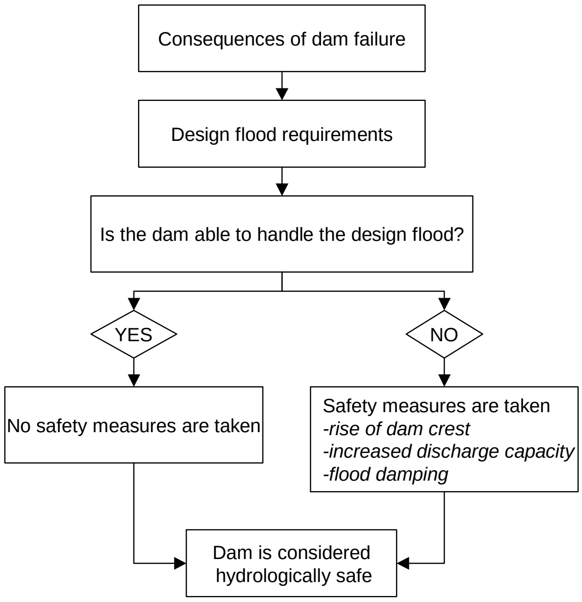

Figure 4.1 ***Management of hydrological dam safety in Sweden today***

There are different methods for determination of the design flood. The flood frequency methods are based on a statistical evaluation of historical flood observations. Distribution functions are fitted to observed extreme values and extrapolated to the desired return periods. Another design method is to maximise the runoff generating factors like precipitation, soil moisture and snow melt and convert these factors to a flood by the use of a hydrological model. A third method is to use empirical rules with an implicit level of safety. An empirical rule where the dams were designed for a flood equal to the highest recorded discharge with an addition of 10 to 20 % were used in Sweden before the Swedish guidelines for flood determination were developed. The doubling of the largest peak flow recorded at the dam site is another of these empirical rules that has been used as design flood around the world.

Each of these methods has its advantages and disadvantages. In Sweden extreme flows are simulated by hydrological modelling maximising the impacts of the flood generating factors. In this chapter the different methods are evaluated. The use of risk analysis as an alternative to design flood determination is also evaluated. The Swedish guidelines for design flood determination are analysed and compared to the spillway design principles in other countries.

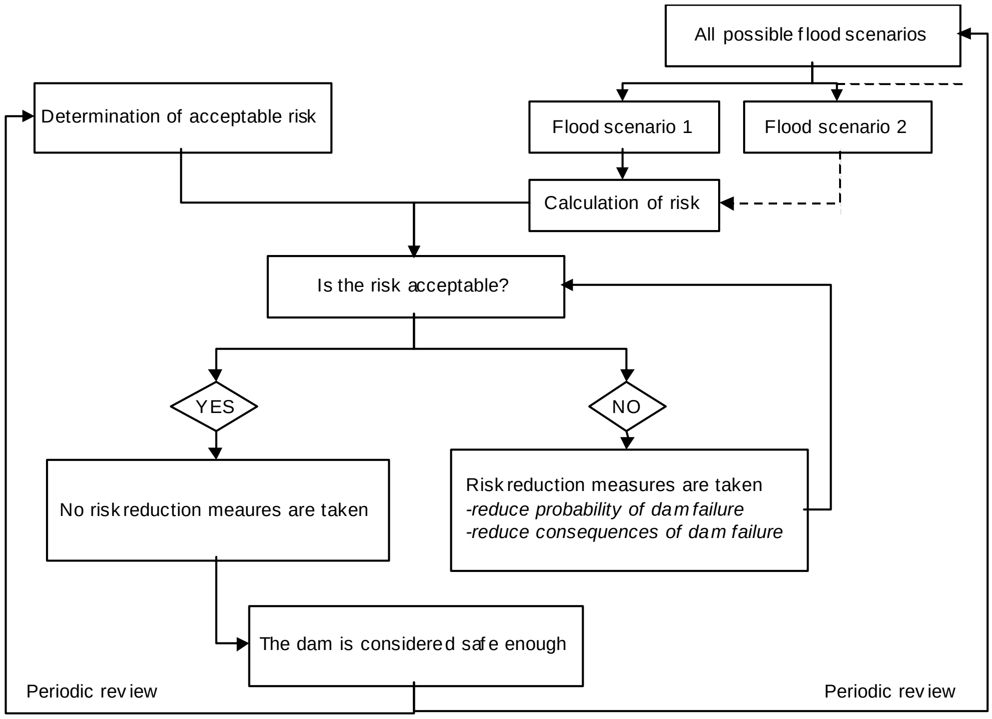

Figure 4.2 ***Management of hydrological dam safety with a risk assessment approach***

4.1 Methods for design flood determination

4.1.1 Historical floods

The study of historical flood events that occurred prior to direct measurements may be used to supplement existing hydrological data. In India, Japan, China and Egypt references exist to floods that occurred more than 1000 to 2000 years ago. In Europe information about catastrophic floods from the time of the Roman Empire can be found.

The problem with historical flood data is the transformation of the water levels to flow rates due to uncertainties of the stability of the flow conditions in the rivers. Practically all historical flood data relate to rivers draining large catchments (some thousands of km^2) (ICOLD 1992).

4.1.2 Flood frequency methods

The flood frequency methods are based on a statistical evaluation of historical flood observations. Distribution functions are fitted to observed extreme values and these functions are extrapolated to the desired return periods. The observed annual maximum floods can be transferred into the annual exceedance probability. If instead all observed floods above a certain level are used the peak over threshold is obtained.

Flood frequency analysis has the advantages that it is simple to apply and specifies the return period of the flood. But there are also problems related to the use of this method.

- Runoff observations over long time periods are often missing. Floods with return periods significantly exceeding the observation length are considered unreliable. In most countries the longest available runoff records are about 100 years long. In order to obtain the flood with a return period of 10,000 years the observations would then have to be extrapolated about 100 times
- Conditions might change so that conditions valid when the observations where made are not valid anymore
- Different distribution functions can be chosen. The problem is that they often give different results for extrapolation

However new approaches for estimating the exceedance probabilities of extreme floods are being developed. In (Van Gelder 1996) an attempt in the Netherlands to make datasets longer by the use of historical data is described and in (Swain et al. 1998) the possibilities to provide scientifically credible probabilistic estimates of extreme floods by combining at-site data with regional data, historical data and paleoflood information are discussed.

4.1.3 Rainfall/runoff analysis

Rainfall records are often longer and more homogenous than runoff records and are therefore often used to predict runoff by the use of a hydrological model.

Compared to frequency analysis the use of hydrological models for determination of design flood has some advantages.

- They can be based on actual hydrological characteristics of the watershed
- They can be calibrated against available data
- They make it possible to adjust to changes like climate change and changes in land use

As well as with flood frequency methods there are however problems connected with rainfall/runoff analysis.

- There is a random variability of hydrological phenomena that has to be dealt with
- The hydrological characteristics of the watershed can be difficult to determine
- It is difficult to determine unique parameter values. The model can function with "wrong" parameter values since different errors might cancel out each other
- Calibration for moderate or high observed floods may not be valid for extreme floods
- Properties of climate and land use may differ from those during calibration of the model
- There may be a lack of observed data for calibration of the model
- The return period of the resulting modelled flood is unknown

4.1.3.1 PMF, Probable Maximum Flood

Rainfall/runoff analysis is used to calculate the Probable Maximum Flood, PMF from the Probable Maximum Precipitation, PMP. PMF is defined as "*the largest flood to be expected assuming complete coincidence of all factors that would produce the heaviest rainfall and maximum runoff*".

The concept of PMP is built on the assumption that there exists an upper physical limit for precipitation. PMP is defined by the World Meteorological Organisation, WMO as "*a quantity of precipitation that is close to the physical upper limit for a given duration over a particular basin*". No return period can be attached to PMP. There are several different methods for estimation of PMP. These methods can be divided in two main groups, statistical methods and meteorological methods (Shaw 1988). In statistical methods records of actual storms are maximised by increasing the observed precipitation by the ratio of the maximum moisture inflow theoretically possible at the site to the actual moisture inflow. In meteorological methods the storm mechanisms causing heavy rainfall are studied and by the use of a storm model the different factors involved are maximised to produce a PMP.

The PMP is converted to the PMF by rainfall/runoff modeling often using the unit hydrograph method. Other critical factors in the watershed like snowmelt and soil moisture are also considered when estimating the PMF.

The PMF is a theoretical flood that has no direct connection to actual conditions and the concept of PMF may lead to the false impression that it is a flood that cannot be exceeded.

4.2 Risk analysis as an alternative to design flood determination

Instead of looking separately at the hydrological load of the dam, risk analysis can be used to integrate the hydrological and hydraulic characteristics with the overall safety factors of the dam. A risk analysis may for instance reveal that a relatively modest flow in combination with some other unfavourable conditions like blockage of the spillway by debris poses a larger risk to the dam than an extreme flood in itself.

Some benefits of using risk analysis for evaluation of dam safety:

- It provides a basis for allocating resources for dam safety improvements
- It improves the understanding of dam performance
- It helps in identifying weak links in a system
- It helps defining and selecting alternatives for dam safety improvements
- The need for additional dam safety investigations can be identified
- It is possible to take into account risk reduction due to warning systems and other non-structural measures
- It is possible to take the special features of the individual dam into consideration
- It can facilitate the communication between different parties like dam owner, dam engineers, authorities concerned and the public

There are however also problems involved when using risk analysis for evaluation of hydrological dam safety.

- The consequences of dam failure often involve loss of lives and environmental damages which are difficult to value in economic terms
- A dam failure has a low probability but can lead to catastrophic consequences and it is not clear how to handle the risk aversion against low probability high consequence risks in a risk analysis
- A detailed quantitative risk analysis requires that the probabilities of different flood events can be estimated. And as described in chapter 4.1.2 the probabilities of extreme floods are very uncertain and difficult to estimate
- A risk analysis can be rather complex and consequently expensive to perform. At the one hand it is for small and middle sized dams that risk analysis could be an alternative to conservative design flood guidelines but on the other hand it is probably only at the large Swedish dams that the dam owner can afford to perform a complete quantitative risk analysis

As with all the other methods for design flood determination, poor input in a risk analysis produces poor output

However one can adjust the level of detail of a risk analysis depending on the purpose and available data and resources. It can range from qualitative descriptions of risk to detailed quantitative analysis. As more data becomes available the risk analysis can be developed to be more and more quantitative and detailed.

The economical resources available for dam safety improvements are limited and different dams and different safety measures have to be prioritised. The use of a risk approach including risk analysis could be a way of securing effective use of available resources.

In order to facilitate and improve the use of risk analysis it is important that all available statistics are used. Rain and flood statistics should be easily accessible as well as data on dam performance during different flooding situations. It is therefore crucial that incidents are documented by the dam owner.

Risk analysis is not a method to obtain an absolute measure of dam safety. Rather it should be seen as a complement to engineering judgement and present design principles and be used in a comparative way. However research in the area is in full progress and since we are only in the beginning of practising risk analysis when dealing with dam safety it is reasonable to expect changes in the application.

4.3 Swedish guidelines for design flood

Until 1990 Sweden had no guidelines for determination of the design flood. However a practice had developed where the dams were designed for a flood equal to the highest recorded discharge with an addition of 10 to 20 %. This often equals a flood with a return period of 100 years when applied in rivers where relatively long flow data were available.

In 1990, the Swedish Committee for Design Flood Determination presented a report with guidelines for determining design floods for dams based on a risk classification of the dams.

The dams are divided in classes based on the potential consequences in case of dam failure, risk class I and II where dams in class I constitutes the highest risk defined as a non-negligible risk to human life or other bodily injury or a clear risk of major economic damage. The design flood for dams in risk class I shall be simulated by applying an accepted hydrological model using a combination of unfavourable meteorological and hydrological conditions. For dams in risk class II the design flood should be the flood with a return period of 100 years, determined by frequency analysis.

4.3.1 Risk classification of dams in Sweden

The risk classification according to the Swedish guidelines for design flood determination is based on dam failure due to high floods only while the consequence classification according to RIDAS (Svensk Energi 2002) also considers dam failures caused by other factors than high floods.

The classification according to the design flood guidelines, see table 4.1, is based on the estimation of a marginal or additional effect of a dam failure, that is the increase in damage due to dam failure compared to the damage caused by the flood itself if the dam had not failed.

Table 4.1 ***Risk classification according to the Swedish guidelines for design flood determination***

Class	Consequences
I	- Non-negligible risk to human life or other bodily injury; or - Considerable risk of serious damage to important infrastructure, dam facility or other similar installation, or an ecosystem of significant environmental value; or - Clear risk of major economic damage.
II	Non-negligible risk of damage to major infrastructure, dam facility or equivalent installation, ecosystem of significant environmental value or property belonging to a party other than the dam owner in other cases than those specified for risk class I.

4.3.2 Design flood determination

The Swedish guidelines use a deterministic approach comparable with the concept of PMF. Though the Swedish method is based on a critical timing of the flood generating factors which have all been experienced but not at the same time or place. When calculating PMF on the other hand, the precipitation is usually increased to values exceeding the observed precipitation.

A 14-day sequence of rainfall data based on the highest observed areal precipitation over an area of 1000 km^2 with adjustments for time of year, region and area is combined with specified snow melt and soil moisture conditions to produce the design flood. Regulation strategies and wind impact is also considered. The maximisation of the flood generating factors is obtained mainly by a critical timing of the different factors and not so much by extrapolation of the single factors.

The procedure for determination of design flood according to the Swedish Committee for Design Flood Determination are summarised below.

Dams in Consequence Class I

The determination of the design flood shall be simulated by applying a hydrological model in the following steps:

1. The model is calibrated against existing runoff series (at least 10 years).
2. By means of frequency analysis, snow storage with a return period of 30 years is calculated. This is entered in the model on the last date on which the snow cover culminates during one of the years analysed.
3. The design sequence of 14-day precipitation according to the Committee´s guidelines is adjusted for actual altitude of the catchment , time of the year and catchment area.
4. Water regulation strategies incorporating the Committee´s guidelines, storage data discharge curves and water conservation regulations as they effect the modeling conditions are entered into the model. Only spillways that can be put into operation at short notice and with full safety are to be included. The storage is assumed to have reached the maximum water level by August 1st and is not assumed to decrease in level until the critical flow period is over. Discharge possibilities through power station turbines may not be included from and including the 9th day of the precipitation sequence.
5. The design flood shall be determined by model simulation for at least 10 years, based on the latest available year´s climatic data. In the simulation, the 14-day precipitation sequence is advanced one day at a time from the date specified in 2 above. The simulation that gives the highest water level in the sequence will be the selected design flood event.

6. The wind impact is determined and added to the design water level in accordance with 5 above.

In addition there is a supplementary condition which states that the discharge capacity of the dam at full supply level shall normally be such that a flow with a return period of at least 100 years can be discharged.

It is assumed that the modeled design flood has a probability of exceedance a specific year of less than 10^{-4} and hence a return period exceeding 10,000 years. A comparison of calculated design flood with the highest observed flood for about 50 different places in Sweden were done (Lindström et al. 1993). In most of the areas the return period exceeds 10,000 years with marginal. Half of the results indicate return periods exceeding 100 000 years. The report points out that it is very difficult to calculate the return period for the design flood with any significant accuracy.

Dams in Consequence Class II

The design flood to be used is a flow with a return period of at least 100 years, determined by means of frequency analysis using existing hydrological data.

4.4 Design flood - international overview

4.4.1 Norway

The Norwegian regulations make a distinction between design flood and safety check flood. The design flood is the flow the dam shall be able to handle under normal conditions, determined by frequency analysis, whereas the safety check flood is defined as an accidental load the dam shall be able to handle without failure. It is calculated by means of values of PMP and a hydrological model.

The dams are classified into three classes according to consequences of failure. Dams in the low hazard class are only evaluated against the design flood while dams in the significant and high hazard class are also evaluated against the safety check flood.

Table 4.2 ***Design flood in Norway (Molkersrød et al. 2001)***

Dam hazard classification	Damage potential: affected dwelling units	Design flood	Safety check flood
Low hazard	0	500-year flood	
Significant hazard	1-20	1000-year flood	PMF or $1.5*Q_{1000}$
High hazard	>20	1000-year flood	PMF

4.4.2 Finland

In Finland the design floods are determined by frequency analysis. The dams are classified into four different classes, P, N, O and T-dams. For dams in the highest class where dam failure poses an obvious danger to human lives, obvious severe societal danger or obvious considerable danger to environment or property, a design flood with a return period of 5000 to 10,000 years should be used (Loukola et al. 1998).

<u>P-dam:</u> If failure occurs the dam poses an obvious danger to human lives, obvious severe societal danger or obvious considerable danger to environment or property.

<u>N-dam:</u> A dam that does not pose such a danger as a P-dam, but on the other hand poses a larger threat than an O-dam if failure occurs.

<u>O-dam:</u> A dam higher than 3 meters that poses only inconsiderable danger. Examples of O-dams are low, distant fish

dams, dams covering only a part of the river and dams used for timber floating that are supervised during timber floating periods.

T-dam: A cofferdam with the purpose of short time lowering of water level.

The recommended return period for the design flood depends on the classification.

Table 4.3 ***Design flood in Finland***

Dam class	Return period (years)
P	5,000 – 10,000
N	500 – 1000
O	100 - 500

The design floods are determined by frequency analysis of measured extreme high flows using Gumbel distribution.

4.4.3. The United States

The different dam owners in the United States use different guidelines for design flood determination. There is a fair consensus on spillway requirements for high hazard dams whereas for dams with lower hazard classifications there is a wide range of criteria being applied (FEMA 94 1998).

The Inflow design flood, IDF, for high hazard dams is often defined as the flood above which the incremental increase in downstream water surface elevation due to dam failure is no longer considered acceptable. The upper limit of the IDF is the PMF.

The U.S. Bureau of Reclamation applies risk assessment when determining the design flood. The consequences and probability of dam failure is considered and the design flood is determined by an iterative calculation.

The present guidelines of the U.S. Army Corps of Engineers are deterministic. Dams where a dam failure implies human life at risk or cause a catastrophic event should be able to safely pass the PMF. New probabilistic guidelines are currently under development at the U.S. Army Corps of Engineers.

4.4.4 The United Kingdom

In the United Kingdom dams are divided into four categories and the design flood depends on which category the dam belongs to. For dams in the highest category the PMF is used (Minor 1998).

Table 4.4 ***Design flood in the U.K.***

Dam class		Design flood
A	Where a dam break could endanger lives in a community	PMF
B	Where a dam failure could i) endanger lives not in a closely populated area or ii) result in extensive damage	0.5 PMF or 10,000 years (take larger)
C	Where a dam break would pose negligible risk to life and cause limited damage	0.3 PMF or 1 000 years (take larger)
D	Special cases where no loss of life can be foreseen as a result of a dam failure and very limited additional flood damage would be caused	0.2 PMF or 150 years

4.4.5 France

In France the Gradex method, Gradient of Extreme Values, is used where frequency analysis is applied with precipitation data instead of runoff data. The precipitation is converted to runoff after reduction for soil moisture deficits. For concrete dams with large risk exposure the 5000-year flood is used while for concrete dams with small risk exposure the 1000-year flood is used. For embankment dams the 10,000-year flood is used (Minor 1998).

4.4.6 Canada

In Canada the rules vary between the different provinces. In British Columbia and Ontario PMP-calculations and hydrological models are used while Hydro Quebec has developed its own method, based on dividing up and redistribution of existing measured precipitation series.

The Dam Safety Guidelines of the Canadian Dam Association state that the Inflow Design Flood, IDF for high consequence dams should be between the 1 000-year flood and the PMF. High consequence dams are dams where some fatalities are expected. The sliding scale was probably intended to provide dam owners some flexibility to use balanced judgement in the determination of IDF. There is however no legal support for selecting anything else but the PMF for high consequence dams (Personal communication - Estergaard).

The validity of applying PMF where it is not reasonable and practicable to upgrade a dam to the PMF is currently being questioned in Canada.

4.4.7 Australia

ANCOLD

Australia is currently the only country that has fully integrated risk assessment in their design flood guidelines. In 2000 the new Guidelines on Selection of an Acceptable Flood Capacity for Dams were published (ANCOLD 2000). In these new guidelines risk assessment is integrated in the determination of design flood.

The Acceptable Flood Capacity, AFC, for a specific dam is defined as "*the overall flood capacity, including freeboard as relevant, which provides an appropriate level of safety against a flood initiated dam failure to protect the community and environment, to acceptable overall risk levels, within the total context of overall dam safety from all load cases*".

The risk process requires the owner, or other decision-maker, to take the responsibility to set the risk management criteria and then to make the decisions on the overall management, community and environment and political and legal issues, using the information provided by the risk study.

According to the AFC Guidelines the hydrological safety should be assessed within the total load context, and not as a separate case, in order to achieve optimum safety and economy and not just concentrate on flood safety.

In cases where a detailed risk process is too costly and not practical the guidelines include a fallback alternative based on a hazard classification with five hazard categories based on the population at risk and the severity of damage and loss.

Table 4.5 and 4.6 show the hazard classification and the fallback alternative for AFC.

Instead of the Inflow Design Flood, Australia has adopted the Dam Crest Flood (DCF) as the basis for comparison of safety. The DCF is defined as the flood event which, when routed through the reservoir, results in a still water level in the reservoir, excluding wave effects, which:

- for an embankment dam is the lowest point of the embankment crest;
- for a concrete dam is the uppermost level of the crest;
- for a concrete faced rockfill dam is the lowest point of the crest.

The provision of freeboard is a matter for consideration for the specific dam, site and consequences of failure.

Table 4.5 ***Hazard categories from ANCOLD Guidelines on Assessment of Consequence of Dam Failure***

Population at Risk	**Severity of Damage and Loss**			
	Negligible	Minor	Medium	Major
0	Very Low	Very Low	Low	Significant
1 to 10	Low Notes 1 and 4	Low Notes 4 and 5	Significant Note 5	High C Note 6
11 to 100	Note 1	Significant Notes 2 and 5	High C Note 6	High B Note 6
101 to 1000		Note 2	High A Note 6	High A Notes 6
>1000			Note 3	Extreme Note 6

Note 1: With a Population at Risk, PAR of 5 or more people, it is unlikely that the severity of damage and loss will be "Negligible".

Note 2: "Minor" damage and loss would be unlikely when the PAR exceeds 10.

Note 3 "Medium" damage and loss would be unlikely when the PAR exceeds 1000.

Note 4: Change to *Significant* where the *potential for one life being lost* is recognised.

Note 5 Change to *High* where *there is the potential for one or more lives being lost*

Note 6 Refer to *Guidelines on Assessment of Consequence of Dam Failure* Section 2.7 and 1.6 for explanation of the range of High Hazard Categories

Table 4.6 ***Fallback flood capacity***

Incremental flood hazard category (IFHC)	**Flood annual exceedance probability (AEP)**
Extreme	PMF
High A	PMF
High B, C	10,000 to PMF
Significant	1000 to 10,000
Low*/Very Low	100 to 1000

*If loss of life is possible, then consider as "Significant"

DSC (the New South Wales Dam Safety Committee)

In New South Wales there is a distinction made between dam failures that occur without any relation to natural flooding and failures that occur in association with a natural flood. These two types of failure give rise to two types of hazard rating:

Sunny Day Hazard rating - based upon the adverse consequences that would result from failure of a dam under normal flow conditions.

Incremental Flood Hazard Category - based upon the incremental adverse consequences that result from failure of a dam during a flood.

Incremental Flood Hazard Category is used for determination of the design flood.

There are three different Hazard ratings, namely High, Significant and Low. An assessment is made on the basis of loss of life consequences only which sets the minimum level of hazard rating. A secondary assessment is then made on the basis of consequences other than loss of life to see whether they justify a higher rating than that based on loss of life.

High Incremental Flood Hazard Category (loss of human life would be expected as the result of dam break) - Acceptable Flood Capacity shall be the estimated PMF based on the PMP.

Significant Incremental Flood Hazard Category (the potential loss of human life is recognised) - Acceptable Flood Capacity shall be in the range of the 1:1000 to 1:10,000 Annual Exceedence Probability flood, but not less than half the estimated PMF.

It is proposed that the DSC guidelines will be revised looking at the new guidelines from ANCOLD.

4.4.8 Germany

In Germany new dam standards are planned to be published. According to them two design floods should be used, Design flood-case 1 for the design of spillways and Design flood-case 2 for dam safety evaluation. The dams are divided in large/middle sized dams and small dams where the distinction goes between a storage capacity of 100 000 m^3 and a dam height of 5 m. Dams should be able to handle Design flood-case 1 without any damage and Design flood-case 2 with intact load-bearing capacity of the dam. However damage to components can be accepted during the case 2-flood. The residual risk due to the possibility of floods exceeding the Design flood-case 2 should also be considered (Deutsche Norm 1999).

Table 4.7 ***Design flood in Germany***

Dam size	Design flood case 1	Design flood case 2
Large and middle-sized dams	1000 year flood	10,000 year flood
Small dams	100 to 500 year flood	1000 to 5000 year flood

4.4.9 Italy

In Italy the flood with a return period of 1000 years is used (Minor 1998).

4.4.10 Spain

In Spain the dams are classified according to size, potential hazard and type of dam. Two different floods are used, the design flood and the extreme flood or safety check flood. For dams in the highest hazard class the 1000-year flood is used as design flood. The extreme flood for dams in the highest hazard class varies between the 5000- and 10,000-year flood, where the higher values should be used for embankment dams. The operation during floods must not produce flows that create damages downstream that are higher than those corresponding to unregulated conditions (Minor 1998).

4.4.11 Switzerland

In Switzerland a design flood with a return period of 1000 years is used. As a safety check the PMF is used, where the PMF in most cases is assumed to be 50 % higher than the design flood (Bundesamt für Wasser und Geologie 2002). For the safety check overtopping of embankment dams is not accepted. For concrete dams overtopping can be accepted.

4.4.12 South Africa

In South Africa envelope curves are used for the determination of design floods. Maximum flood peaks observed in a hydrologically homogeneous region are plotted against catchment area and an envelope curve is drawn for the points. The curve is considered as the upper limit of expected flood peaks for the considered region. The corresponding flood peak is called Regional Maximum Flood, RMF, and is the flood used when evaluating the safety of a dam. The envelope curves are based on 519 maximum observed flood peaks in South Africa, Lesotho Swaziland, Namibia, Botswana, Zimbabwe and Mozambique (ICOLD 1992).

For spillway design the 200-year flood is used.

4.4.13 Austria

Due to the fact that practically all of the dams in Austria pose a risk of loss of human lives, the large dams have not been classified with regard to hazard. Large dams are dams higher than 15 m above foundation level or reservoirs with a capacity of more than 500,000 m^3. The spillways should be designed for a 5000-year flood. Studies concerning PMF methods have been carried out, but the calculation of PMF are extremely difficult for small catchments in mountainous regions (Melbinger 1998).

4.4.14 The Netherlands

In the Netherlands a water level that the dikes must be able to withstand is prescribed. The country is divided into different dike ring areas where each dike ring area is an area protected by a linked system of primary dikes. The standard is expressed as the mean yearly exceedance frequency of the prescribed water level. It varies from 1/10,000 to 1/1,250 depending on the economic activities and size of population in the protected area.

A new safety approach based on the risk of flooding is under development. With this new approach the risk is expressed by multiplying the probability of flooding with its consequences, meaning that the safety can be increased not only by strengthening of the dikes or by lowering of the extreme water levels, but also by affecting the potential effects of flooding (Méndez 1998).

In the ongoing Floris project, Flood Risks and Safety in the Netherlands, that was started in 2001, the probability and consequences of flooding for all dike ring areas in the Netherlands are to be calculated (Ministry of Transport, Public Works and Water Management). Together with the calculation of probabilities and consequences of flooding, existing hydraulic structures will be assessed and special attention will be given on how to handle the uncertainties connected with the project results.

4.4.15 The Czech Republic

The dams in the Czech Republic are classified into three classes, A, B and C. For dams belonging to class A the lives of ten or more persons are endangered while for class B the lives of single persons are endangered. For dams in class C there is no probable loss of life. For class A dams the 10,000 year flood is used as design flood while for class B dams the 1000-year flood is used. The flood with a return period of 100 years is used for dams belonging to class C (Macháček 1998).

4.5 Comparison between design flood in Sweden and international practice

Approximately 85 % of the dam spillways in the world have capacities that are based on the PMF or the 10,000-year flood according to Fahlbusch (Fahlbusch 1999). Of the countries mentioned above Norway, the United States, the United Kingdom and Canada use the PMF as design flood for the dams in the most serious risk class. The countries in Southern Africa use a design flood called the Regional Maximum Flood, RMF, based on over 500 observed maximum flood peaks.

Australia uses a risk-based approach where the overall dam safety is considered and not just the hydrological load. In the United States the Bureau of Reclamation already use risk assessment whereas the Army Corps of Engineers are currently developing probabilistic guidelines. In Canada and the Netherlands a risk-based approach is under development.

The other countries use a design flood based on frequency analysis with a return period varying between 1000 years and 10,000 years. Some countries like Norway, Spain, Germany, Switzerland and South Africa make a distinction between the spillway design flood and the flood used for dam safety evaluation.

The Swedish design flood for dams in consequence class I can be compared to a PMF. Though the Swedish method is based on a critical timing of the flood generating factors which have all been experienced but not at the same time or place. When calculating PMF on the other hand, the precipitation is usually increased to values exceeding the observed precipitation.

There is no common principle used internationally when dealing with design flood. Instead each country has its own way of handling the design flood. Some countries use probabilistic methods while others use deterministic and some use a different flood for design than for safety evaluation. For countries using probabilistic methods the return period of the design flood is in the range of 1000 to 10,000 years. Freeboard should be accounted for in some countries whereas in others no consideration is taken to it. And in some countries a higher design flood is required for embankment dams than for concrete dams. The comparison of design flood between different countries is thus ambiguous. Conditions like properties of watersheds and dams, climate and density of population living downstream differ between the countries and different cultures have different objectives and policy for handling safety and risks. Therefore it is probably not reasonable to expect common design flood guidelines to be developed that are applicable to all countries. The differences could also be seen as a reflection of the uncertainty connected to extreme floods.

A common feature is that no country seems to make any significant distinction between new and existing dams.

4.6 Analysis of the Swedish guidelines

4.6.1 Deterministic versus probabilistic methods for design flood determination

In a deterministic method the chance of occurrence of the variable involved is ignored and the method used is considered to follow a definite law of certainty, and not probability. Deterministic guidelines often use safety levels that are based on extreme events that are considered highly improbable but from a physical point of view possible, as an estimated limited value like the PMF. This principle is used in Sweden when determining the design flood.

In Australia, Canada, the United States and the Netherlands new probabilistic guidelines have recently been developed or are currently under development. The Bureau of Reclamation in the United States emphasizes that there has been an increasing trend in water resources analysis towards probabilistic design methods for evaluation of the effectiveness of different safety measures (US Bureau of Reclamation 1997).

In his paper "Should dams be modified for the probable maximum flood?" Graham objects to the use of PMF for dam safety modifications due to the following reasons: (1) larger spillway capacity may increase annual downstream flood losses, (2) benefit-cost ratios may be low, (3) construction accidents associated with dam modification may cause fatalities, and (4) the amount spent to save lives by making dams safer is often very high (Graham 2000).

Probabilistic methods have the advantage over deterministic methods that they give an estimation of the probability of dam failure and they integrate the uncertainty. This is necessary if risk assessment is to be fully used. The problem is that the probabilities in question when dealing with extreme floods are so small and accordingly difficult to estimate.

The design flood for class I dams in Sweden is often referred to as the 10,000 year flood. This is a simplification. Since the guidelines are based on a deterministic method there is no return period connected with the design flood.

For an existing dam that has been evaluated by means of the Swedish guidelines you can tell if it fulfils the requirements in the guidelines or not, but you can not estimate the level of residual risk. Even when the most restrictive design criteria are applied the risk of dam failure, although very small, can never be totally dismissed. On the other hand the Swedish guidelines are not so dependent on statistical data and can be adjusted to account for changes of the hydrological properties in a watershed, changes of the climate and changes of the regulation strategies.

4.6.2 Classification of dams

To some extent a risk approach is used in the Swedish guidelines when dividing dams into consequence classes. However the classification only considers the consequences and not the probability of a possible dam failure. Since the guidelines only use two consequence classes, major differences in the severity of consequences due to dam failure between dams in the same class is possible. Because the classification system is coarse it does not help the dam owner in his allocation of resources for dam safety measures.

The terms used for describing the risks that a conceivable dam failure would pose are negligible-, non-negligible-, considerable- and clear risk. How these terms are valued are open to subjectivity. One person may assign the same value to considerable risk as another person does to clear risk. Rating words open to subjective interpretations like high, obvious and considerable are used internationally as well when dividing dams into different classes.

Two different principles can be used when dealing with dam safety. One approach is to define a minimum safety level that shall be fulfilled no matter what the costs are. Another way is to start with available resources and make sure they are used most effectively to ensure safe dam performance. Dam safety management has an important perspective of ethics. Can loss of human lives be evaluated in economical terms? The safety level that can be achieved is depending on available resources for implementing safety measures. The guidelines state that the risk of dam failure shall be brought down to a level as low as possible with present knowledge, available technique and reasonable economical costs. In order to evaluate what is the level of reasonable economical costs, an economical analysis has to be carried out taking both probability and consequences into account. Since the economical resources of the power industry available for dam safety improvements are not unlimited, priorities need to be considered between different dams. Is it then reasonable that the economical costs involved in fulfilling an acceptable safety level is the same for a dam where a dam failure may lead to the loss of one life as the costs for a dam where a dam failure may lead to the loss of several lives. Should the costs for dam safety measures be independent of the probability of dam failure? The Swedish national road administration puts a value on human life in order to make priorities between different safety measures. So why could it not be done when dealing with dam safety?

It is essential that the classification of dams reflects the reality as much as possible. The use of say five consequence classes would better reproduce the real situation than the use of only two classes. A risk assessment taking both consequences and probability of a dam failure into account for the individual dam gives an even better picture of reality. The problem is that the closer to reality the dam safety guidelines get the more difficult it may be to apply in practice.

Should an existing warning system be accounted for when classifying the dams? A well functioning and reliable warning system will lower the risk posed to human lives. A warning system will on the other hand not have a major effect on the probability of failure. A warning system provides an extra safety factor. However, like the dam itself, the warning system is vulnerable to impacts from extreme weather conditions. You can never guarantee 100 % reliability of a warning system but it seems unreasonable not to consider the existence of warning systems at all when performing the risk classification since in fact a well functioning warning system can lower the consequences of dam failure considerably.

4.6.3 Precipitation sequence

The Swedish design flood guidelines are based on a 14-day precipitation sequence. Depending on the properties of the watershed a precipitation sequence with a different duration may pose a higher risk. In large watersheds with a high presence of natural lakes and reservoirs, rains with a lower intensity but longer duration may be more critical and in small watersheds rains with a higher intensity but a shorter duration than the 14-day sequence may be more critical. A review of the guidelines with reference to their application for large lakes like Vänern and for small watersheds is currently under work.

4.6.4 Small versus large dams

In Sweden there are approximately 10,000 dams of which about 190 are higher than 15 m (Bartsch 1995), the definition of a large dam according to ICOLD.

In 1973 a filling dam at Sysslebäck in Sweden failed. Although the dam height was only about 4 m, one life was lost. In 1989 a very old dam in Cheshire, England failed. The dam was only about 5 m high but the failure resulted in one life being lost. These are only two examples of small dams that have failed with loss of life as a consequence. Even though a dam failure of a small dam will not lead to a catastrophe the consequences can be severe with large damages and even loss of lives.

Statistics from dam failures in the United States between 1960 and 1998 (in total more than 300 fatalities) show that 2 % of the deaths were caused by failure of dams less than 6.1 m high and 86 % of the deaths were caused by failure of dams between 6.1 and 15 m high (Graham 1999).

The failure of a large dam would in most cases lead to more severe consequences than if a small dam should fail. But this does not necessarily mean that the risk is always higher for large than for small dams. Some facts listed below leads to the conclusion that it is likely that our large dams are in a better condition than the small ones.

- The pre-investigations, design and construction of a large dam is likely to be more detailed and thoroughly worked through than for a small dam
- Control and supervision of large dams is more extensive than for small dams

- Large dams have larger financial resources for dam safety improvement measures than small ones
- Many small dams are owned by private persons who neither have the resources nor the knowledge to maintain a high dam safety
- Construction drawings and other documentation is more likely to be found for large dams than for small ones

Simplified one could say that the consequences of dam failure are higher for large dams whereas the probability of dam failure is higher for small dams.

A problem encountered when dealing with the safety of small and medium dams is the difficulty to finance the dam safety measures. For small dams belonging to risk class II it is easier to fulfill the guidelines for design flood determination since it is considered sufficient that they can handle a 100-year flood. The difficulty of fulfilling the guidelines comes when dealing with small dams lying somewhere between class I and class II dams since the costs for dam safety management can differ significantly depending on if the dam is classified as a class I or class II dam. The ability to finance dam safety measures cannot however be allowed to determine the safety level. If the costs for fulfilling a tolerable risk level are impossible or unreasonable to finance, decommissioning of the dam should be considered.

The guidelines for design flood determination were initiated by the power industry. Accordingly they have been formed to suit large hydropower dams that are often a part of a large river system with several dams. For small class I dams not being a part of a larger system the cost for calculating the design flood is very high whereas for the large rivers in the North of Sweden the cost for design flood calculation can be spread over many dams.

4.6.5 Reservoir characteristics

The Swedish guidelines do not only consider the magnitude of the incoming flood but also take into account damping in the reservoir and to some extent regulation strategies and initial water level. Besides they consider wave run up and inclination of water level. According to the Swedish guidelines the water level in the reservoir should be assumed to have reached full supply level on August 1st at the latest. This is to guarantee that the reservoir is able to handle the design flood during all circumstances. Depending on the actual initial water level when the flood reaches the reservoir this assumption provides an unknown additional safety margin.

In a risk analysis, consideration could be taken to the probable water level at the single reservoir when evaluating the hydrological safety instead of assuming that it has reached full supply level on August 1st.

4.6.6 Climate change impacts

The uncertainties connected to predictions of future runoff patterns considering a climate change are substantial. However considering the results from climate modelling so far a future scenario with an increased frequency of the most extreme floods does not seem to be probable. Instead it seems like a global warming of the climate would even out the most extreme floods. However a change in the seasonal flood pattern is likely to happen. The spring flood will be advanced in time and smaller while the floods during late summer and autumn probably will increase. Even during winter, high floods are possible in the future. High floods in autumn and winter can be troublesome since this is the time when the reservoirs are full. A normal high flood in combination with a full reservoir may pose just as high a risk as an extreme spring flood. During winter when there is still ground frost a heavy rain can lead to a very fast runoff response. And there is not much vegetation that can absorb water. Besides autumn and winter floods are less predictable than the spring flood, which might lead to an increased uncertainty in the flood estimates. Another factor affecting the flood capacity of the dams is that a warmer climate might possibly lead to stronger winds.

A possible advantage with the present Swedish guidelines compared to flood frequency methods is that they may be easier to adjust to a climate change.

4.6.7 Possible alternatives for design flood determination in Sweden

The Swedish risk classification system with two classes could be extended to more classes. As an example the Australian fallback alternative uses five hazard classes where a distinction is made between the number of lives at risk induced by a dam failure.

There should exist an alternative for the dam owner to use risk assessment of the overall safety of the dam. And based on the results the dam owner should be able to choose another flood than the one prescribed in the Swedish guidelines for control of the dam safety. In this way greater consideration could be taken to the existence of warning systems and emergency plans. And more consideration could be taken to the special features of the single dam. In this respect more research in the field of assigning probabilities to extreme hydrological events would be desirable.

The guidelines should be revised for instance every fifteen years to take into account changes that occur.

5 CONCLUSIONS

One of the major risks posed on dams is the hydrological load. Statistics show that 1/3 of all dam failures were caused by overtopping. There are many different ways of decreasing the hydrological load on a dam such as:

- increasing the spillway capacity,
- rising the dam crest,
- diverting the flood to less sensitive areas,
- implementing local flood mitigation measures in the watershed or
- changing the reservoir regulation strategies.

Strongly connected to the hydrological dam safety is the design flood determination. In 1990 guidelines for determination of design flood were published in Sweden. The design flood to be used for dams where a failure would imply loss of human lives is calculated by using a combination of unfavourable meteorological and hydrological conditions in a hydrological model. There is no return period connected to the design flood but comparisons with highest observed floods at a number of places have given that in most cases the return period of the design flood exceeds 10,000 years with margin. A comparison of international practice show that there is no common principle for design flood determination. There seems to be a certain tendency towards using risk analysis for evaluation of hydrological safety. Australia is however the only country that at present has fully integrated risk assessment in their design flood guidelines.

The Swedish dams are currently being adjusted to fulfil the requirements according to the Swedish guidelines for instance by reconstruction of spillways or rise of dam crests in order to damp the extreme floods. It is not an easy task to handle since there are many different interested parties with different objectives involved. Damping in the reservoir for instance may cause upstream flooding whereas increased spillway capacity may lead to downstream flooding.

In a flooding situation the main objective must be to secure the safety of the dams since a dam failure could lead to catastrophic consequences. However, as far as possible one should strive for an integrated flood management where all aspects are considered, like risk of upstream- and downstream flooding, risk of dam failure etcetera, trying to find the best solution from a total point of view where the consequences of the flood is mitigated as far as possible. All affected parties and not only the dam owner should be informed and offered to participate in the decisions on flood management strategy. It is essential that the different alternatives are thoroughly evaluated in order to avoid unpleasant surprises during a flooding situation.

From a total dam safety perspective it can be questioned whether it is optimal to upgrade all class I dams to safely handle the design flood according to the guidelines for design flood determination. It is likely that in some cases those resources could be used on other dam safety measures that more efficiently should decrease the risk of dam failure. The ideal would be if the hydrological dam safety instead of being looked at separately is integrated with the overall dam safety. And that the uniqueness of each dam and its environment could be fully integrated in the dam safety evaluation. A complete application of risk management in this way is probably not possible in practice – at least not in the nearest future. Deterministic guidelines are probably necessary at least as a complement to risk management in order to guarantee a fairly uniform minimum national level of dam safety.

The long-term objective in Sweden should be that the guidelines for design flood determination are complemented with a possibility to use risk assessment for evaluation of the hydrological dam safety. A risk approach would make it possible to take greater consideration to the individual features of the single dam. And it would make it possible to take into account non-structural risk reduction like the existence of warning systems. For the dam owner a risk assessment would help in allocating resources for dam safety improvements.

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DAM SAFETY EVALUATION IN SALA

Tina Fridolf

2004

TABLE OF CONTENTS

SUMMARY

The city of Sala has an old water system that used to belong to the Sala Silver Mine. The water system contains several dams of which some are more than 400 years old. Two of these dams have been classified as risk class I dams and the hydrological safety of these dams is not considered adequate according to the Swedish guidelines for design flood determination. A risk assessment approach is used for evaluation of the dam safety with the objective to find a reasonable strategy for handling the dam safety in the area with focus on the hydrological safety.

Specifically the following questions are analysed:

- Risk sources - The different risks posed to the dams in Sala are described by event trees and the importance of the different events are analysed
- Consequences and probability of dam failure - The consequences of dam failure are estimated based on an interview with the Rescue Service and an approximate dam break calculation. The probability of dam failure due to hydrological loading is roughly estimated based on the results from hydrological modelling of the water system.
- Tolerable risk level – The question of tolerable risk is discussed and reference is made to international praxis
- The applicability of the Swedish design flood guidelines considering the special features of the dams in Sala – The special features of the dams in Sala that could have an effect on the choice of design flood are analysed. Compared to hydropower dams the dams in Sala are much older, classified as cultural historical monuments, small scale dams, not regulated with respect to power production factors, manually operated and not associated with economic benefits
- Risk reduction measures – The dam safety in Sala can be increased by:
    - Diverting the floods
    - Rising the dam crests
    - Implementing regular dam safety inspections, comprehensive dam safety reviews and providing a manual for operation, maintenance and supervision
    - Introducing warning system, emergency preparedness plan and evacuation plan
    - Relocating summerhouses downstream of the dams
    - Increasing the spillway capacity
    - Implementing flood mitigation measures in the watershed

The advantages and disadvantages of the different risk reduction measures are analysed.

1 INTRODUCTION

In the city of Sala, located in the central part of Sweden, 110 km west of Stockholm, silver mining was going on for many centuries and in order to secure the supply of waterpower needed for the mining, an extensive water system with dams, canals and regulations were implemented.

When the municipality of Sala took over the water system in 1989, it became clear that the dam safety did not comply with the Swedish guidelines for design flood determination.

The oldest dams were built already during the 16th century and are classified as historical monuments, meaning that the alternatives for major reconstructions are restricted.

A risk assessment approach is used for evaluation of the dam safety in Sala with the objective to find a reasonable solution for handling the dam safety in the area with focus on the hydrological safety.

Specifically the following questions are analysed:

- Risk sources
- Consequences and probability of a dam failure
- Tolerable risk level
- The applicability of the Swedish design flood guidelines considering the special features of the dams in Sala
- Risk reduction measures

2 THE SALA WATER SYSTEM

2.1 History

The water system for the mine was built in three stages 1504-1543, 1595-1660 and 1819-1822. During the first stage Långforsen, Silvköparen and Olov Jons dam were constructed in order to secure the power supply for the ore refining. During the 16th century waterpower was more and more used for the mining for example for driving pumps and the increased need for water resulted in the construction of the second stage of the water system which comprised Storljusen, Stensjön and Långsjön. During this stage the natural watercourse was reversed by construction of a 6 km long channel from Storljusen to Silvköparen named Ljuse grav. In order to make the water flow south in direction to the mine the channel had to be as deep as 6 m at some places. During the third and last construction period Helgonmossen and Björnmossen were linked to the system. The water system now comprised 27 lakes with a water area of 1600 ha of which about 1000 ha were inundated mires. The total length of the channels was about 25 km. The power from the entire water system has been estimated to only about 29 kW (Engelbertsson 1991). When the mining stopped in 1908 there was no longer any need for water power, however the historical value of the system was early recognised and it was decided to preserve the water system.

Parallel to the water system of the mine a water system was constructed for the foundry. The main part of this system has however been dried up for a long time.

2.2 Water system characteristics

The water system in Sala is a small scale system consisting of lakes, dams, gated discharge facilities and channels. The dams consist of long earth walls just a few metres high and often covered with trees. At several places where water used to be stored the discharge facilities have been removed, see figure 2.1.

There are five major lakes/reservoirs, Storljusen, Stensjön, Silvköparen/Olov Jons dam and Långforsen. Silvköparen and Olov Jons dam are connected via a culvert under the road. During flooding situations the culvert limits the flow leading to a difference in water level between the two lakes. The area contributing with runoff to Långforsen is approximately 84 km^2. The water level difference between Storljusen and

Långforsen of approximately 26 m whereas the water level difference between Stensjön and Långforsen is approximately 16 m.

The water system has a great value as a recreational area and as a historical monument.

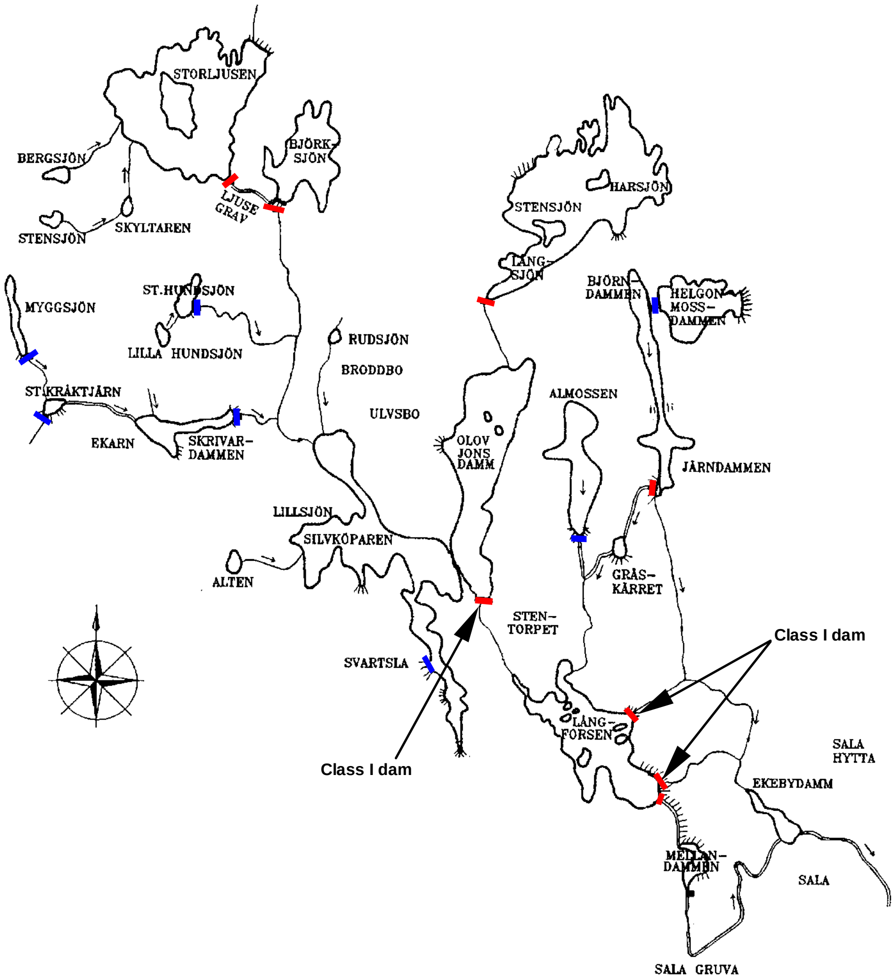

Figure 2.1 ***The water system of Sala. Present regulation facilities are marked with red whereas removed regulation facilities are marked with blue.***

2.3 Risk classification of the dams

A classification of the dams was performed by SMHI in connection with an analysis of the design flood in 1994. Olov Jons dam and Långforsen were classified as class I dams. At first Storljusen was also classified as a class I dam because of a nearby rock cavern for storage of aircraft fuel that had its regulation of level connected to the water level of Storljusen. Since the storage room has now been dismantled and cleared of oil, the dam of Storljusen has been reclassified to a class II dam. Stensjön has been classified as a class II dam.

2.4 Description of the class I dams

According to a summary of the reservoirs of the water system the total available storage volume is 16 405 000 m^3 (Sundholm 1932). Since this data is almost 70 years old it should be taken only as an approximate value. The data in table 2.1 is given by the Public building administration, unit Street & Park in Sala.

Olov Jon´s dam is probably founded on uncovered natural moraine according to an investigation from 1996 (Nilsson et al. 1996) and the rock surface might have been reached at some sections. The dam of Långforsen is founded partly on natural moraine and partly on rock. The dam bodies consist of moraine material. The upstream and downstream slopes of the dams are protected against erosion with a stone layer. To a varying degree the dams are covered with trees.

Figure 2.2 ***Part of Olov Jons dam***

Figure 2.3 ***Part of Långforsen***

Table 2.1 ***Data of Långforsen and Olov Jons dam***

	Långforsen	**Olov Jons dam**
Type	Embankment dam	Embankment dam
Length	~300 m	~ 700 m
Crest Width	~2,5 m	~ 4 m
Height	0-4 m	0-5 m
Area at full supply level	~2,65 km^2	~ 2,01 km^2
Storage volume at full supply level	~ 1,85 million m^3	~ 4,34 million m^3
Normal water level	+65,21	+71,85
Full supply level	+65,61	+72,57
Dam crest	+65,81	+72,60
Number of spillways	3	1 ordinary + 1 emergency

2.5 Discharge facilities

The discharge facilities in Sala are manually operated during floods. Below follows a description of the discharge facilities of the class I dams. There does not exist any water regulation act for the water system.

Olov Jons dam

The discharge facilities at Olov Jons dam consist of one ordinary and one emergency spillway. The maximum discharge through the ordinary spillway is 4,5 m^3/s at full supply level. The capacity of the emergency spillway is 1,8 m^3/s at full supply level. However this flow causes flooding of summerhouses situated downstream. In order not to cause any downstream consequences only 0,3 m^3/s can be discharged through the emergency spillway. The gate at the ordinary spillway is operated approximately 30 times a year.

Approximate calculations of the rate of water level increase during a risk class I flood shows that with the gates closed it takes about 9 hours until the water level has reached the dam crest from an initial normal water level. At maximum discharge (4,5 m^3/s) the time before the dam crest is reached is increased by approximately 1 hour. The maximum discharge capacity constitutes only about 10 % of the risk class I flood.

Figure 2.4 ***Discharge facilities at Olov Jons.***

Figure 2.4 ***Discharge facilities at Olov Jons.***

Långforsen

The discharge facilities at Långforsen consist of three spillways at Dammboski, Krokforsen and Serveringen. Maximum discharge at full supply level at Dammboski is 2,3 m^3/s, 2,0 m^3/s at Krokforsen and 0,3 m^3/s at Serveringen. The gate at Dammboski is operated approximately 15 times a year while the gate at Krokforsen is operated on an average 20 times a year. The gate at Serveringen is operated approximately 4 times a year.

Figure 2.5 ***Discharge facilities at Dammboski, Långforsen.***

Figure 2.6 ***Discharge facilities at Krokforsen, Långforsen.***

Figure 2.7 ***Discharge facilities at Serveringen, Långforsen.***

Calculations of the rate of water level increase during a risk class I flood shows that with the gates closed it takes 7 to 8 hours until the water level has reached the dam crest from an initial normal water level. At maximum discharge (4,5 m^3/s) the time before the dam crest is reached is increased by approximately 30 minutes. The maximum discharge capacity constitutes about 10 % of the risk class I flood.

The Public building administration, unit Street & Park in Sala has suggested a rise of the dam crest to level +65,95. The time before overtopping occurs is then increased by approximately 2 hours during a risk class I flood.

Regulation strategies

During a normal year 24 millions m^3 of water is discharged from the water system. During the year 2000 though, 38 millions m^3 was discharged from the system. During high flow situations all three gates at Långforsen are fully opened and the discharge from Olov Jons is regulated to keep the full supply level in Långforsen.

2.6 Incidents

A minor dam breakthrough in a smaller dam at Långforsen occurred in the end of the 1980ies. The leakage was stopped with dolomite (used for putty production in Sala) that has a cementing effect due to its lime content. A dam breakthrough at Storljusen has also occurred. The exact time of this event is unknown but it was probably during the 1950ies or 1960ies. When the municipality of Sala took over the water system, the spillway capacity at Långforsen was improved. Earlier the water levels during the snowmelt period often nearly reached dam crests in Långforsen and Mellandammen.

During November 2000 a flood estimated as a 25-year flood by SMHI occurred in Sala. According to the responsible engineers at the municipality this flood was handled without any incidents but the margin before overtopping of the dam crests was small.

2.7 Organisation and emergency preparedness

The Public building administration, unit Street & Park has the operative responsibility of the dam safety, while the unit Water & Wastewater/Planning has the management responsibility. There is no special emergency preparedness plan for the water system but the Rescue service in Sala together with the Public building administration has preparedness for emergency events and actions within the limits of the ordinary activity. According to the Public building administration this is however not sufficient enough at larger emergency actions.

2.8 Earlier studies

A study concerning determination of the design flood and the corresponding water levels in the water system was performed by SMHI in 1994 (Olofsson et al. 1994). The Swedish guidelines for design flood determination were applied and the HBV model was used for the hydrological modelling. The design flood situation, that is, the situation that resulted in the highest water levels during modelling was August 1987. The resulting water levels exceeded the dam crests by more than 0.5 m at Storljusen and by more than 1 m at Stensjön, Olov Jons dam and Långforsen.

The hydrological model was also run with a rainstorm equal to 70 % of the design rainstorm. The resulting water levels exceeded the dam crests of Olov Jons and Långforsen by about 0,1 m.

Since no measured flow data for the watershed was available at the time of the study the hydrological model was calibrated against data from another, unregulated watershed. In order to improve the knowledge of the hydrology of the water system it was decided to start measuring the flow at a number of sites. Flow measurements started in 1996. However the measurements were not carried out on a continual basis but only in connection with regulation of the reservoirs when the measuring points were visited. Based on this new flow data a new hydrological modelling was carried out by the Hydraulic Department at the Royal Institute of Technology. The modelling is described in the report "Hydrologisk modellering av Sala Silvergruvas vattensystem" (Fridolf 2003).

3 RISK ASSESSMENT

Although the water system of Sala is small it is complicated in the sense that is consists of many lakes, dams, and discharge facilities that interact. And when evaluating the safety all parts of the system have to be considered.

Money spent on dam safety measures in Sala leaves less money for other socially beneficial projects since the funds of the municipality are limited. It is therefore essential to use resources for dam safety improvements as efficiently as possible.

The water system is evaluated by using a risk approach in order to find a reasonable safety level for the dams.

3.1 Purpose

The purpose of the risk assessment is to:

- Elaborate on the risks associated with the dams so that the municipality, the public and other interests get a clear picture of the situation
- Estimate the effects of different risk reduction measures
- Assist in decisions on risk reduction measures
- Be a support for the municipality when determining about tolerable risk

3.2 Limitations

- The risk analysis is not a complete quantitative risk analysis
- Focus has been on the risks induced by high floods

3.3 Potential risk sources:

Although this study concentrates on the risk posed on the dams by high and extreme floods it is important to point out that there are other risk sources that may pose an even greater risk to the dams. Possible risk sources are listed below.

A. Extreme floods - An extreme flood may lead to overtopping of the dam crests and a resulting dam failure. Overtopping of the dams will with high probability cause a dam failure.

B. Leakage through the dams - Ongoing leakage through the dams may lead to internal erosion and finally to dam failure.

C. Trees growing on the dam crest – Uprooting may lead to extensive damage and leakage through the dam, which in turn may result in dam failure. Most of the trees are already cut down, but the remaining roots still constitute a risk source. Along the roots leakage can develop through macro-pore flow leading to piping. Roots that stop growing can lead to development of cavities in the dam. According to Hoskins and Rice (Hoskins et al. 1992) trees growing on embankment dams may in some cases have a positive effect on dam safety by improving the slope stability and an example is given of a 200 year old dam where the instability increased after all the trees were removed.

Figure 3.1 ***Trees growing on the dam crest of Långforsen.***

D. Floating debris - The spillways may be blocked by debris preventing full discharge. During an extreme flood it is probable that debris is produced since there is a lot of trees in the area. The risk of floating mires should also be considered. Since the dam gates in Sala are small it is not likely that the debris will pass through freely.

E. Gates are not opened – which can be caused by:

- Lack of observation – Water level observations in the reservoirs are done manually. During autumn and spring the dams are inspected on a daily basis, while in summer the dams are inspected once a month except during heavy precipitation when they are visited more often. Since there is no automatic measuring of water levels it is possible to miss some high floods. And even if the high floods are observed they may not be observed in due time to open the discharge facilities, warn the rescue service and evacuate the public
- Gates getting stuck - The discharge facilities are regulated manually on a need basis. It is possible that the gates are left unregulated for long periods which may result in these gates getting stuck and being very difficult or even impossible to open when necessary. Floating debris can be another reason for the gates being very difficult to open
- Non-trafficable roads - High floods and the need for emergency actions often coincide with bad weather situations like strong wind, snow and high precipitation. A bad weather situation may make it impossible to reach the discharge facilities and dams. Some of the dams in Sala are very difficult to reach due to bad or non-existent roads

F. Human factor - The observations of water level and the operation of the discharge facilities are done manually which makes the dam safety of Sala highly dependent on the human factor. The fact that the entire water system is operated manually can lead to resource problems during a flooding situation.

A dam failure caused by uprooting trees or internal erosion can happen very suddenly whereas a dam failure due to overtopping is likely to be preceded by a period of much rain or snowmelt. Consequently the time for warning and evacuation is probably larger for a dam failure caused by extreme floods. On the other hand an extreme flood will likely cause problems at several places in the area and its surroundings at the same time meaning that available resources for rescue and safety has to be divided. An extreme flood is also likely to cause secondary effects like broken transmission lines and broken access roads making emergency actions more difficult.

A fault tree with top event “Dam failure” has been constructed for the dams in Sala.

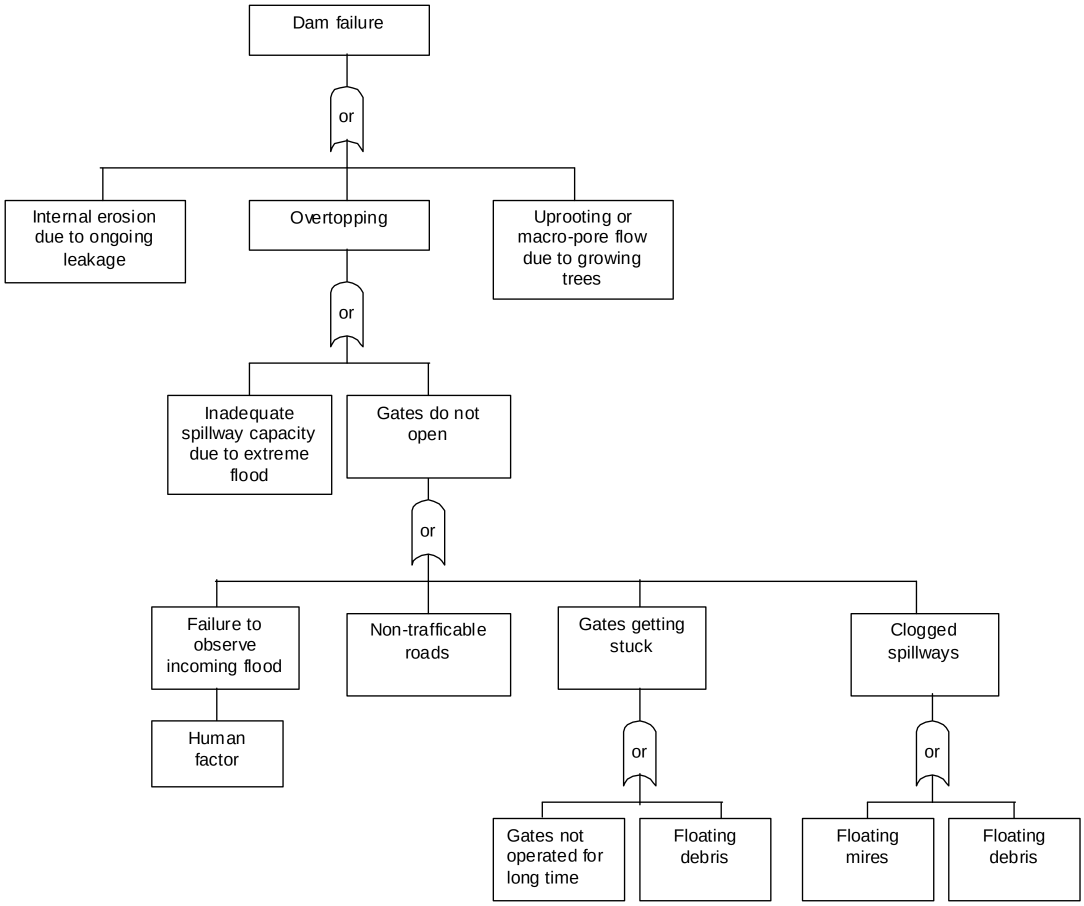

Figure 3.2 ***Fault tree with top event "Dam failure" for the dams in Sala***

3.4 Event tree analysis

Event trees have been constructed for the risks posed by high/extreme floods, leakage through the dam, trees growing on the dam crest and debris in the watercourse.

Since this paper deals specifically with hydrological dam safety the only scenario that has been further analysed is the one with high/extreme floods leading to dam failure.

The existence of other risks however show that even if the water system is rebuilt to safely pass the design flood for instance by implementing flood diversions, refurbishment and upgrading of the dams can not be excluded.

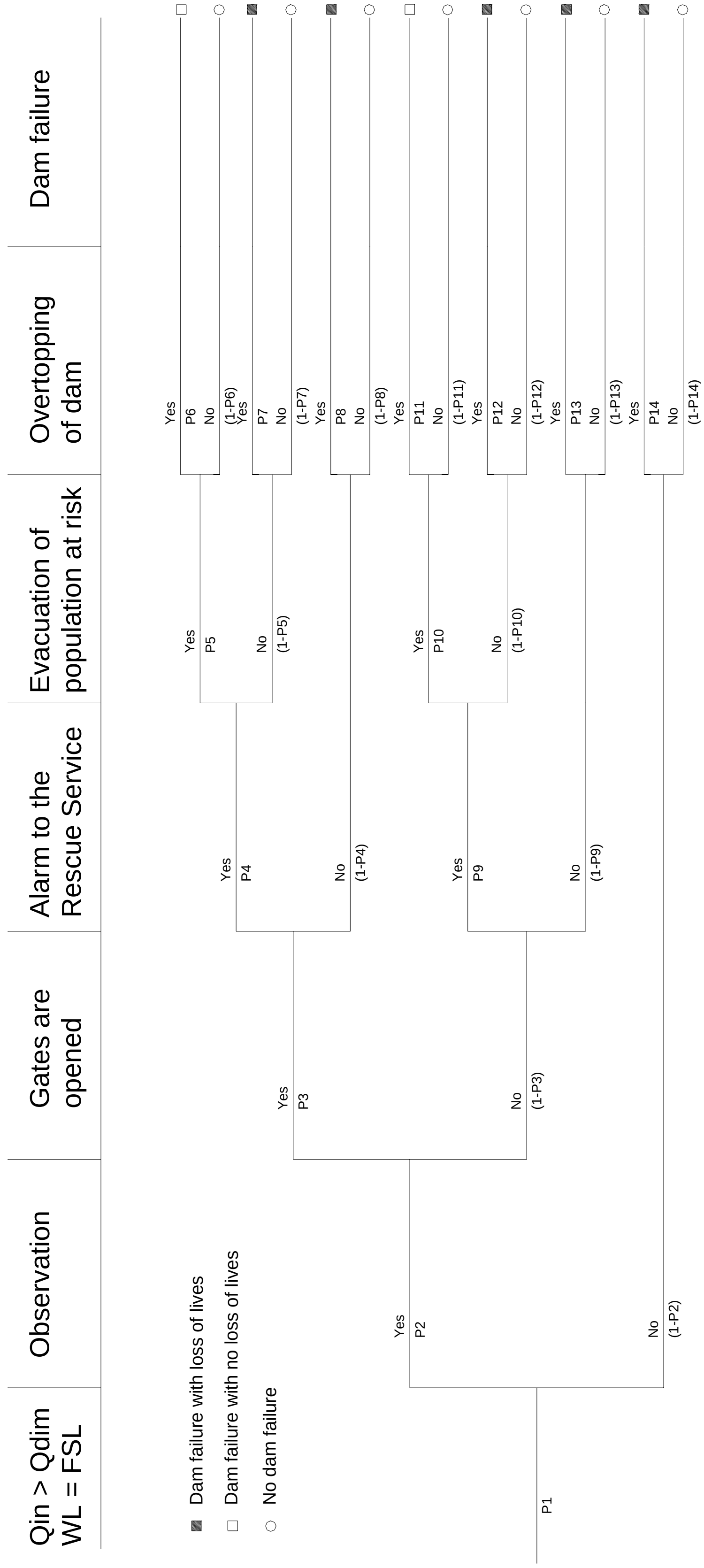

Figure 3.3 ***Event tree for initiating event Q_{in} > Q_{dim} (FSL=Full supply level)***

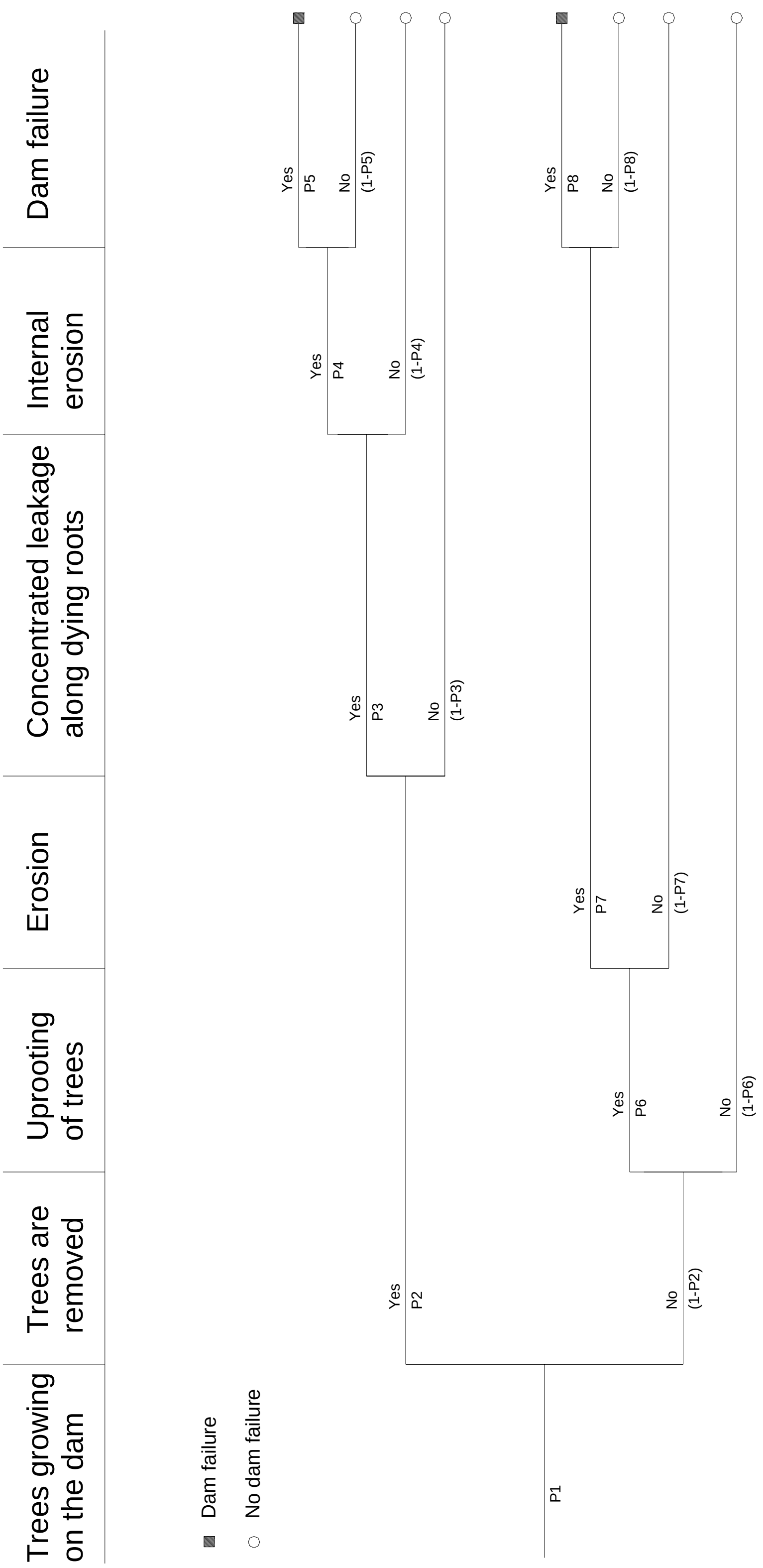

Figure 3.4 ***Event tree for initiating event Trees growing on the dam***

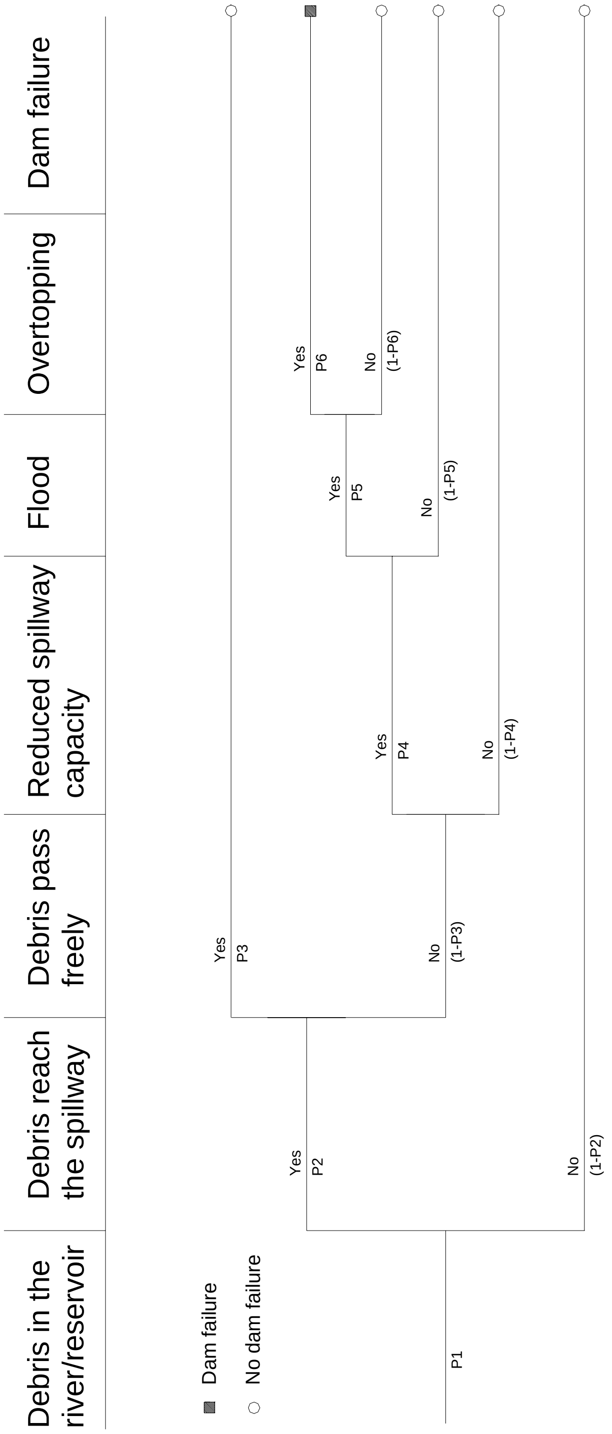

Figure 3.5 ***Event tree for initiating event Debris in the river/reservoir***

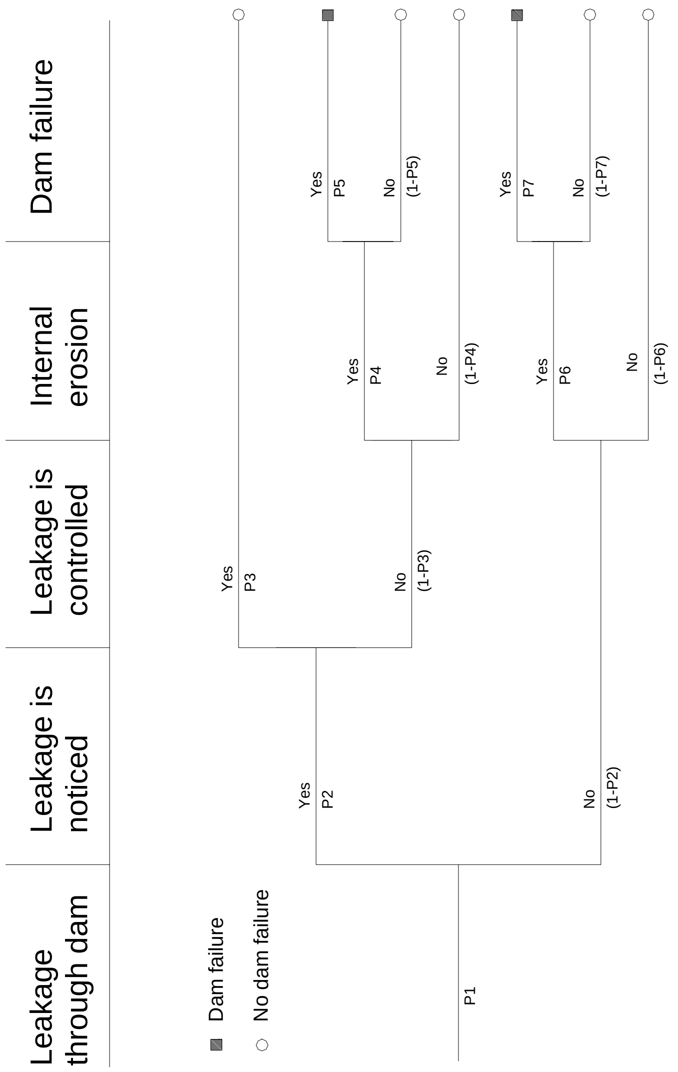

Figure 3.6 ***Event tree for initiating event Leakage through dam***

3.4.1 The significance of the different events

Probabilities have been assigned to the single events in the event tree in figure 3.3 with initiating event Q_{in} = 100-year flood. The assessed probabilities for the events “observation of flood in due time”, “gates are opened” and “alarm to Rescue Service” have then been changed one at a time. The purpose has been to evaluate how a change in the probability of a single event affects the probability of the final event - dam failure with loss of life as a consequence. The probabilities in table 3.1 are subjective probabilities or “best guesses” based on engineering judgement and should be used only in the context of evaluating the significance of the different single events and not for estimating the probability of dam failure in Sala.

Table 3.1 ***Assessed probabilities for event tree in figure 3.2 with initiating event Q_{in} = 100 year flood***

EVENT	EVENT DESCRIPTION	ASSESSED PROBABILITY 1, AP1	AP2	AP3	AP4
1	100-year flood	P_1=0.01	0.01	0.01	0.01
2	Observation of flood in due time	P_2=*0.9*	0.9	*0.5*	0.9
3	Gates are opened	P_3=*0.9*	*0.5*	0.9	0.9
4	Alarm to Rescue Service	P_4=P_9=*0.9*	0.9	0.9	*0.5*
5	Evacuation of downstream population	P_5=P_{10}=0.5	0.5	0.5	0.5
6	Overtopping with open gates	P_6=P_7=P_8=0.9	0.9	0.9	0.9
7	Overtopping with gates closed	P_{11}=P_{12}=P_{13}=P_{14}=0.99	0.99	0.99	0.99
A	Dam failure	$P_A=P_1 \bullet P_2 \bullet P_3 \bullet P_4 \bullet P_5 \bullet P_6+$ $P_1 \bullet P_2 \bullet (1-P_3) \bullet P_9 \bullet P_{10} \bullet P_{11}=$ 0.0092	0.0095	0.0095	0.0092
B	Dam failure with loss of lives	$P_B=P_1 \bullet P_2 \bullet P_3 \bullet P_4 \bullet (1-P_5) \bullet P_7+$ $P_1 \bullet P_2 \bullet P_3 \bullet (1-P_4) \bullet P_8+$ $P_1 \bullet P_2 \bullet (1-P_3) \bullet P_9 \bullet (1-P_{10}) \bullet P_{12}+$ $P_1 \bullet P_2 \bullet (1-P_3) \bullet (1-P_9) \bullet P_{13}+$ $P_1 \bullet (1-P_2)=$ **0.0055**	**0.0057**	**0.0074**	**0.0071**

As can be seen in table 3.1 a change in the probabilities of the flood being observed in due time or the Rescue Service being alarmed affects the probability of dam failure with loss of lives more than a change in the probabilities of gates being opened.

Since the maximum discharge capacity only constitutes about 10 % of the risk class I flood, the operability of the gates is important but not crucial during an extreme flood. The time difference before dam crest is reached (initial water level = normal water level) if gates are fully opened compared to if they are closed is only about 1 hour for Olov Jons and 30 minutes for Långforsen.

A rise of the dam crest of Långforsen according to proposal from the municipality in Sala, increases the time from normal water level to overtopping by approximately 2 hours for Långforsen during maximum discharge.

More important than being able to open the gates are to observe a rise in water level at an early stage and to have a well functioning warning- and evacuation system.

3.5 Consequences of a dam failure

A dam failure can be associated with catastrophic consequences. The extension and severity of these consequences may be difficult to estimate in advance and depends on the special features of the dam in question as well as the features of the downstream area. The consequences are also highly dependent on the characteristics of the dam break. Possible consequences of a dam failure are:

- Loss of human lives and injuries
- Environmental damages
- Economic damages – Damages on infrastructure and lost power production
- Bad publicity – After the flooding in parts of Sweden in July 2000 the public criticised the power industry for not taking their responsibility. It is not difficult to imagine the criticism that would follow a major dam failure

The consequences of a dam failure of the dams of Olov Jons and Långforsen have been estimated. It should be pointed out that this is only a rough estimation. If Olov Jons dam fails several millions m^3 of water will be released. The total water volume of Silvköparen and Olov Jons dam at full supply level is 6 millions m^3. The flood wave will hit the summerhouses just downstream of the dam and then continue down towards Långforsen and the national highway. The water volume at full supply level in Långforsen is 1.85 millions m^3. At a dam failure caused by an extreme flood both Olov Jons dam and Långforsen will most certainly collapse, in other words several millions m^3 of water will flow down and cause flooding in the city of Sala. Even if only Långforsen should break, 1 to 2 millions m^3 of water will flow down to the city of Sala. The houses downstream Långforsen will be hit by the flood wave which will then continue towards the city of Sala situated only about 3 km downstream of Långforsen.

Loss of human lives and injuries – Sala has approximately 22 000 inhabitants. The summerhouses situated directly downstream Olov Jons dam will be hit by the flood wave following a dam failure and approximately 10 to 20 lives are in danger here according to the Rescue Service in Sala. If the dam at Långforsen should fail approximately 10 lives would be at risk since there are summerhouses and a few permanent houses situated just downstream of the dam. The Rescue Service does not however estimate that a dam failure would lead to loss of lives in the city-centre of Sala. There is a possibility that a part of the water will flow south along the national highway. The road is heavily loaded with traffic during the winter sports holiday and if a dam failure should occur during that time there is a possibility of traffic accidents with loss of lives and/or injuries.

The US Bureau of Reclamation has published guidelines for estimating loss of life caused by dam failure. According to the guidelines that are based on data from floods and dam failures in the United States loss of life is highly related to the warning issued to the people at risk (Graham 1999).

Environmental damages - The dams in Sala have a major value as recreational area and as historical monuments and a dam failure would lead to the destruction of an important piece of the industrial history of Sweden.

Economic damages – There will be no economic losses due to lost power production in the Sala case. Neither are there any large industries in the area that can be damaged by a dam failure. The summerhouses and permanent houses situated immediately downstream of the dams are likely to be flushed away and damage on the national highway is probable. The Rescue Service estimates that the damages in the city will be in the order of hundreds of million SEK.

Bad publicity – The risk of bad publicity is probably not crucial in this case since the dam owner is a municipality. However a dam failure can cause the public to loose confidence in the local politicians of Sala.

3.5.1 Dam break analysis

Dam break analysis for Olov Jons and Långforsen has been done according to the Dam safety guidelines of Washington State Department of Ecology (Washington State Department of Ecology 1992). For more sophisticated calculations a hydraulic model like DAMBRK or FLDWAV could be used. However based on the small size of the dams and the sparse data available, the simplified method is considered sufficient in this case.

For Långforsen with an assumed dam breach height of 2 m the calculation gives a peak flood during dam failure in the range of 900 m^3/s. For Olov Jons the same assumption concerning dam breach height gives a flood peak due to dam failure in the range of 1000 m^3/s. Assuming a bed slope of 0.007 (based on the difference in water level between Långforsen and Ekeby dams) the time before the flood wave caused by a dam break of Långforsen reaches the city of Sala varies between 60 and 90 minutes. The time before the flood wave caused by a dam break of Olov Jons reaches Långforsen is only about 10 minutes. In other words the time for evacuation after dam failure has happened is very short.

Although the dam break calculations are very uncertain and approximate they clearly indicate that a dam failure of Olov Jons dam or Långforsen would cause serious damages in the city of Sala and that the risk of human lives can not be dismissed. Besides it should be noted that a dam failure of Olov Jons would probably lead to a dam failure of Långforsen as well leading to even worse consequences.

3.6 Probability of a dam failure

In order to estimate the probability of a flood-induced dam failure at Långforsen or Olov Jons dam the return period of the design flood has to be estimated.

Since flow measurements in the water system of Sala did not start until 1996 there are no long data series to use in a frequency analysis.

However continuous data of measured precipitation exist from 1961 and forward. These data have been used in a frequency analysis to estimate rain with different return periods. The produced rains have then been used in a hydrological model in order to evaluate the resulting floods. The analysis and the results are further described in "Hydrologisk modellering av Sala silvergruvas vattensystem" (Fridolf 2003). Running the model resulted in overtopping already with a 100 year precipitation sequence and a 30 year rain seems to be about the upper limit of what the water system can safely handle. Assuming that overtopping leads to dam failure this indicates that the probability of dam failure due to flooding can be as high as 0.01 a particular year. If the other risk sources described in chapter 3.3 are also considered the probability of dam failure is even higher.

3.6.1 Available resources during an emergency situation

The resources of the Rescue Service in Sala for preventing dam failure are limited. Excavators exist but it takes about one hour before they can be in operation at the dams during a leakage. Due to the former mining there is filling material available but it must be transported a couple of kilometres. The Rescues Service estimates that when all resources and material are at place at the dam it probably takes a couple of hours before a leakage is stopped.

3.7 Tolerable risk level

In the ICOLD bulletin on risk assessment (ICOLD 2001) acceptable risk is defined as *"a risk which, for the purposes of life or work, everyone who might be impacted is prepared to accept assuming no changes in risk control mechanisms"*. Tolerable risk is defined as *"a risk within a range that society can live with so as to secure certain net benefits. It is a range of risk that we do not regard as negligible or as something we might ignore, but rather as something we need to keep under review and reduce it still further if and as we can"*. According to (Bowles et al. 2003) tolerable risk, rather than acceptable risk is becoming generally accepted as the goal for risk management.

When setting tolerable risk goals the traditional engineering assessment approach uses standards and current good practice as a basis whereas the risk assessment approach uses tolerable risk guidelines (Bowles et al. 2003). Satisfying current engineering practice does not guarantee that tolerable risk will be achieved. On the other hand, tolerable risk may be met with less extensive risk reduction measures than are needed to meet engineering practice.

Internationally there are different examples of countries that have developed or are developing life safety tolerable/acceptable risk criteria. Some countries like Australia, the Netherlands and South Africa use F/N diagram for determination of acceptable risk where F stands for the probability of failure and N stands for the number of fatalities in case of failure. As an example figure 3.5 shows the F/N diagram used in Australia (ANCOLD 2000). The criteria used by the US Bureau of Reclamation (US Bureau of Reclamation 1997) are summarised in table 3.2.

In addition to quantitative risk criteria the ALARP principle, As Low As Reasonably Practicable, is well established for risk management. ALARP can be interpreted as the condition when the costs of additional risk control are grossly disproportionate to the risk reduction benefits gained (ICOLD 2001).

Tolerable risk cannot be given as an absolute quantitative value. What is tolerable today may not be a few years from now and what is tolerable to one society may not be to another. Besides, up today there does not seem to be any practically useful method for determining neither the probability of dam failure nor consequences in case of dam failure with any accuracy.

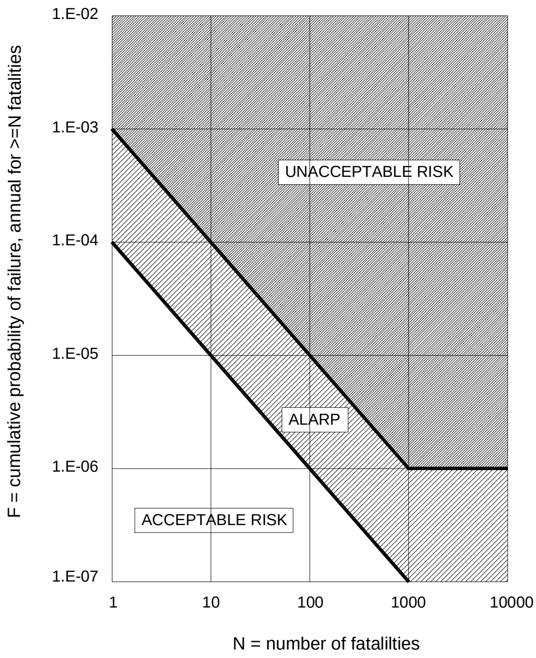

Figure 3.5 ***F/N diagram used by ANCOLD***

Table 3.2 ***Summary of the risk acceptance criteria used by the US Bureau of Reclamation***

ESTIMATED AVERAGE ANNUAL LOSS OF LIFE	
n>0.01	Strong justification to take action to reduce short term and long term risk
0.01>n>0.001	Strong justification to take action to reduce long term risk
n<0.001	Justification for reducing risk decreases – evaluate effectiveness of risk reduction

During a risk evaluation it is important to include in the costs and benefits of risk reduction measures not only easily estimated economical factors and loss of lives but also factors more difficult to estimate like destruction of social structure, trauma, injuries, environmental damages and bad publicity.

Who is to make the decision about tolerable risk? One way is to let government decide by the force of law. Another is to let the dam owner decide about tolerable risk for the individual dam. A third option is to let the risk takers make the decision. What speaks for making regulations is that it insures a minimum safety level and prevents major differences in safety level between different risk sources in society. What speaks for letting the dam owner decide is the individuality of each dam and situation. An obligation on the dam owner to motivate the choice of tolerable risk together with strict responsibility would probably lead to reasonable safety levels. There is however a risk that available resources of the dam owner will guide the choice of tolerable risk.

According to the Swedish guidelines for design flood determination any loss of life due to dam failure is unacceptable. And in case of dam failure in Sala the fatalities are estimated to 10 to 30 lives. The requirement that Olov Jons and Långforsen should be able to safely handle a class I design flood is in line with risk acceptance criteria abroad.

In Sala the determination of tolerable risk has to be a political decision where the politicians should consider the different possible scenarios and then based on available resources, costs for dam safety upgrading, historical/recreational value of the dams, moral aspects, public opinion etcetera make a decision. Preferably the citizens of Sala should be involved in the decision making process. What is obvious is that the risks posed by the dams today are not tolerable.

3.8 Determination of design flood

For dams where a dam failure would result in loss of human lives the design flood used in most countries vary between the flood with a return period of 10 000 years and the PMF (Probable Maximum Flood). Since the Swedish guidelines use a deterministic method for the design flood there is no return period associated with it. However the return period has been estimated on the average to exceed the 10 000 years flood. The Swedish guidelines for design flood determination are only guidelines that the power industry in Sweden voluntarily has decided to follow. In other words they are not legally binding. Accordingly there is no law forcing the municipality of Sala to follow the guidelines. However in case of an incident or dam failure it can be troublesome to motivate that the guidelines have not been followed.

The question is whether it is reasonable to require that the dams in Sala should be able to handle the class I-design flood. Can the special features of the dams in Sala motivate the choice of a flood different than the class I design flood for managing the safety of the water system?

The Dam safety guidelines of Washington State Department of Ecology (Washington State Department of Ecology 1992) contains a procedure based on rating points, for selection of design/performance goals for critical project elements like inflow design flood. The procedure considers dam height, value of the reservoir, the magnitude of dam break flood peak compared to the 100 year flood peak, population at risk including future population increase, warning time, likelihood of observation, evacuation possibilities and downstream property at risk. If this procedure is applied to the class I dams in Sala the Annual Exceedance Probability, AEP of the inflow design flood should be in the range of 10^{-4}.

3.8.1 Seasonal pattern of runoff

In Sala there is a seasonal pattern of runoff with three typical major flood events each year – once during winter, once during spring and once during autumn. The winter flood is caused by a combination of mild weather and rain and possibly ground frost while the spring flood, characterised by a fast and intensive runoff, is caused by a combination of snowmelt and spring-rain. The autumn flood is caused by autumn-rain in combination with a low evapotranspiration.

Any major problems with floods during summer have not been experienced in Sala, not even during the large rains of July 2000. Instead large rains during autumn/winter are considered a more serious risk since the rain in combination with saturated grounds, very low interception and evapotranspiration, snowmelt and possibly ground frost can produce very large floods.

If the predictions of a warmer climate and increased precipitation comes true the seasonal pattern of runoff may change with increased frequency and magnitude of the winter and autumn floods and a decreased and advanced spring flood. During recent years a tendency towards a flood situation around the turn of the year have been noticed. Whether this is a result from a climate change or within the variation of the existing climate is however too soon to say. But it is not unlikely that the flooding risks in the area will increase in the future.

3.8.2 Uncertainties

When evaluating the hydrological safety of the dams in Sala there are several uncertainties to consider both regarding the probability and consequences:

- The capability of the dams to withstand overtopping
- The hydrological modelling of the watershed
- Random variability of hydrological properties
- Future climate change
- The probability of the calculated design flood
- The consequences of a dam failure
- The effectiveness of warning/evacuation in case of dam failure

3.8.3 Threshold flood

The flood experienced during November 2000 with an estimated return period of 25 years can be considered as a threshold below which no structural damage or adverse consequences are expected.

3.8.4 Special features of the dams in Sala compared to hydropower dams

Below are listed the special features of the dams in Sala.

- The dams are much older than the Swedish hydropower dams. Construction of the dams in Sala started already during the early 16th century while the majority of the high hydropower dams in Sweden were constructed during the 1950s, -60s and -70s (Killingtveit et al. 1995).
- The dams in Sala are classified as cultural historical monuments.
- The dams are small. The highest section of Olov Jons dam is 5 m and the highest section of Långforsen is 4 m.
- The reservoirs are relatively small. The total reservoir volume of Långforsen, Olov Jons and Silvköparen is approximately 8 millions m^3. The largest Swedish reservoir, Suorva has a volume of 6000 millions m^3.
- The flows are small. The design flood in Sala according to the Swedish guidelines for flood determination is in the range of 50 m^3/s while the design flood for some class-I dams in the larger rivers in the north of Sweden can reach values exceeding 2500 m^3/s (Lindström et al. 1993).

- The reservoir regulation is not controlled by power production factors.
- The dams are manually operated.
- The dams are not associated with any economic benefits.

Even though there are differences between the dams in Sala and hydropower dams the Sala case can be applicable also to hydropower dams. There are many small hydropower dams in Sweden and the question of finding a reasonable safety level is as important for these hydropower dams as for the dams in Sala.

3.8.4.1 Age and historical values

The lakes of Långforsen and Olov Jons/Silvköparen were dammed already before 1528 to a level lower than the current and during the period of 1595 to 1660 they were risen to their present level. How does the fact that these dams are over 400 hundred years old affect their safety? The lack of documentation from construction of the dams is somewhat compensated by the experience gained from the behaviour of the dams during their over 400 years long existence.

On the one hand you can argue that since the dams have stood there for several hundred years without failure they are safe. On the other hand you can argue that during all these years some deterioration of the dams is probable to have happened. Statistics from 220 earth dam failures in the United States during the period 1850-1950 show that the major part of dam failures have occurred during the first years after completion of the dams (Washington State Department of Ecology 1992). 50 % of the dam failures happened within 5 years of completion and only 1 % of the dam failures happened 50 to 100 years after completion.

For the people living downstream the age of the dam does of course not matter in case of dam failure. Their houses will be flooded irrespective of if the dam was constructed a year ago or 400 years ago.

There are other mining districts in the world that like Sala have water systems with old dams. Connected to the mines in the German Harz mountains over 110 storage reservoirs with a total storage capacity of approximately 10 million m^3 were built between 1535 and 1808 (Schnitter 1994) and the construction of some of these dams might have been influenced by the dams in Sala. Another historical mining district with old dams is Banská-Stiavnica in Slovakia. The water system was constructed between 1614 and 1800 and consisted of 54 reservoirs with a total storage capacity of approximately 7 million m^3. And near Potosí in Bolivia a water system containing 30 reservoirs was constructed during 1573 to 1621. It had a total storage volume of approximately 6 million m^3. In 1626 one of the dams failed, releasing 400 000 m^3 of water and drowning about 4000 people. The total storage volume of the water system of Sala is approximately 16 million m^3. It could be interesting to gather data from these different areas of old mining dams and compare them with respect to incidents, dam failures, implementation of dam safety measures etcetera.

In the book “A history of dams” (Schnitter 1994) there is a list of 12 ancient dams that was in operation for over 2000 years and some of them are still operating. So maybe not too much emphasis should be put on the age of the dams in Sala.

3.8.4.2 Scale effects

The water system in Sala is small-scaled compared to many other areas in Sweden where the guidelines for design flood determination are applied. The question is whether these scale effects influence the validity of the design flood guidelines. Scale effects in Sala that might influence the hydrological dam safety are; the size of the watershed, the size of the dams and reservoirs, the size of rivers and canals in the system and the size of the downstream river.

The guidelines for design flood determination consider scale effects in the area reduction factor of the dimensioning precipitation sequence. Maybe consideration should also be taken to the watershed size when determining length and distribution of the precipitation sequence.

According to a report on climate change impacts on runoff and hydropower in the Nordic countries the flood risk in large, continental catchments can possibly be expected to be reduced, while the flood risk in small catchments can increase (Saelthun et al. 1998). Flood volumes over longer duration show less increase or more reduction than daily mean flood which means that large reservoirs will be less vulnerable to climate change impacts than small reservoirs. Following this a climate change could have a large impact in Sala.

Size of watershed

The size of the watershed contributing with runoff to Långforsen is approximately 84 km^2. For comparison Table 3.3 lists the areas of some watersheds where SMHI has determined the design flood according to the Swedish guidelines. In the same table the value of the design spring flood and the design autumn flood is given. The table is taken from the report "Uppföljning av Flödeskommitténs Riktlinjer" (Lindström et al. 1993).

Table 3.3 ***Calculated design floods according to the Swedish guidelines, sorted after descending size of watershed. (Lindström et al. 1993)***

Watershed	River	Area of watershed (km^2)	Design flood spring (m^3/s)	Specific design flood spring ($l/s \cdot km^2$)	Design flood autumn (m^3/s)	Specific design flood autumn ($l/s \cdot km^2$)
Sikfors krv	Piteälven	10797	2367	219	1360	126
Höljes	Klarälven	5980	1500	251	-	-
Sveg	Ljusnan	5860	2327	397	1352	231
Sourva	Luleälven	4681	2730	583	-	-
Trängslet	Dalälven	4483	2006	447	1464	327
Torpshammar	Ljungan	4229	584	138	309	73
Lannavaara	Torneälven	3882	2054	529	1303	336
Torsebro krv	Helgaån	3676	738	201	573	156
Blankaström	Emån	3446	535	155	335	97
Parki	Luleälven	2596	1210	466	989	381
Satisjaure	Luleälven	2324	1260	542	-	-
Tjaktjajaure	Luleälven	2267	1996	880	1752	773
Malgomaj	Ångermanälven	1757	1037	590	740	421
Niavve	Luleälven	1700	1159	682	962	566
Storjuktan	Umeälven	1656	843	509	553	334
Sädvajaure	Skellefteälven	1444	1558	1079	1307	905
Virihaure	Luleälven	1384	817	590	639	462
Torrön	Indalsälven	1369	1470	1074	1201	877
Lossen	Ljusnan	1353	738	545	602	445
Moholm, Tidan	Vänern, Göta älv	1172	370	316	303	259

WATERSHED	RIVER	AREA OF WATER-SHED (km²)	DESIGN FLOOD SPRING (m^3/s)	SPECIFIC DESIGN FLOOD SPRING ($l/s \cdot km^2$)	DESIGN FLOOD AUTUMN (m^3/s)	SPECIFIC DESIGN FLOOD AUTUMN ($l/s \cdot km^2$)
Karats	Luleälven	1159	423	365	280	242
Ersbo	Dalälven	1101	595	540	492	447
Solberg	Umeälven	1051	798	759	589	560
Kultsjön	Ångermanälven	1050	790	752	754	718
Ytterholmen	Råneälven	1004	642	639	392	390
Sitasjaure	Luleälven	982	1029	1048	-	0
St Blåsjön	Ångermanälven	965	848	879	596	618
Storsjön	Ljungan	928	730	787	634	683
Fulunäs	Dalälven	882	367	416	328	372
Hammarby	Mälaren, Norrström	876	195	223	111	127
Hassela	Harmångersån	658	378	574	279	424
Överuman	Umeälven	630	925	1468	814	1292
Storsjouten	Ångermanälven	625	496	794	411	658
Ransaren	Ångermanälven	578	602	1042	489	846
Grundsjön	Ljusnan	566	514	908	420	742
Borgasjön	Ångermanälven	508	471	927	395	778
Ankarvattnet	Ångermanälven	430	404	940	317	737
Lofssjön	Ljusnan	398	317	796	270	678
Abelvattnet	Umeälven	370	416	1124	339	916
Källstorp	Ljungbyån	344	75	218	56	163
Ljusnedal	Ljusnan	340	273	803	223	656
Vässinjärvi	Dalälven	340	262	771	206	606
Simlången	Fylleån	263	112	426	109	414
Tänndalen	Ljusnan	233	160	687	111	476
Äcklingen	Indalsälven	157	174	1108	147	936
Ö. Särvsjön	Ljusnan	157	155	987	126	803
Storrensjön	Indalsälven	119	140	1176	140	1176
Burvattnet	Indalsälven	117	158	1350	136	1162
Gårdsilt	Fylleån	55	31	564	30	545
Långforsen	*Sala*	*84*	-	-	*~50*	*~595*

The watershed of Långforsen is small compared to watersheds of other class I-dams in Sweden. Of the 49 watersheds in the table only one has an area smaller than 100 km². The size of the watershed influences the amount of runoff produced. The larger the watershed the larger the amount of produced runoff. The size also influences the damping of the flood, since the larger the watershed the longer the time of concentration. Statistics from dam failures in the United States show that failure of dams with a drainage area less than 26 km² caused 75 % of the deaths (Graham 1999). The same statistics also show that warning prior to dam failure was less likely where the drainage area was small.

(Lindström et. al 1993) examined the ratio of the highest observed flood and the design flood for the watersheds in table 3.3. They found that the ratio was fairly independent of watershed size.

An overview of the Swedish guidelines is currently going on and one component deals with design flood determination for small watersheds. Intensive rains with a short time scale and small room scale are being analysed.

Size of dam

For comparison figures of dam height for the highest dam in the world, the highest dam in Europe and the highest dam in Sweden are given below.

Table 3.4 ***Height of class I dams in Sala compared to some large dams***

DAM	COUNTRY	TYPE	HEIGHT (M)
Rogun	Tadjikistan	Earth- and rock fill	335
Grande Dixence	Switzerland	Concrete gravity	285
Trängslet	Sweden	Rock fill	125
Långforsen		Earth fill	4
Olov Jons dam		Earth fill	5

Size of reservoar

For comparison some figures of reservoir volume of three of the largest reservoirs in northern Sweden are given below.

RESERVOIR	VOLUME (million m^3)
Suorva	6000
Seitevare	675
Satisjaure	260
Långforsen	*1,85*
Olov Jons dam	*4,34*
Silvköparen	*1,66*

Some examples of reservoir volume criteria internationally are also given. The size classification applied in the US (ICOLD 1992) defines a large dam as a dam with a reservoir capacity of more than 61,5 million m^3. According to this classification Långforsen, Olov Jons dam and Silvköparen would be classified as intermediate. In Austria dams with a reservoir volume exceeding 500 000 m^3 are defined as large dams (Melbinger 1998) whereas in Germany the distinction goes at reservoir volumes exceeding 100 000 m^3 (Deutsche Norm 1999). In Switzerland the regulation for dams complies to dams with a height exceeding 5 m and a reservoir volume exceeding 50 000 m^3 (Bundesamt für Wasser und Geologie 2002).

4 RISK REDUCTION

Risk reduction can either be obtained by reducing the probability or the consequences of dam failure. Of the risk reduction measures described below dam inspection, comprehensive dam safety review, manual for operation, maintenance and supervision, rise of dam crest, increased spillway capacity and implementation of flood diversion reduce the probability of dam failure whereas warning system, evacuation plan and relocation of summer houses reduce the consequences but not the probability.

4.1 Inspections, comprehensive dam safety reviews and manual for operation, maintenance and supervision

According to RIDAS, the dam safety guidelines of the Swedish power industry (Svensk Energi 2002), dams belonging to the highest consequence class, 1A, should be inspected by an inspector with relevant competence every third year. Regular dam safety inspections are a rather cheap way of improving dam safety.

To perform a comprehensive dam safety review is another important dam safety measure. According to RIDAS a comprehensive dam safety review should be performed every 15th year for dams belonging to class 1A and every 24th year for dams belonging to class 1B.

To keep a manual for operation, maintenance and supervision that contains all documentation necessary for the safe operation, maintenance and supervision of the dams is another important safety measure.

4.2 Warning system, emergency preparedness plan and evacuation plan

A warning system and an evacuation plan are necessary since no absolute guarantee against dam failure can be given. An emergency preparedness plan should be developed and the population living downstream of the dam should be informed that during certain circumstances their lives can be in danger, even if dam safety measures are implemented. When a dam failure is a fact, warning- and evacuation systems will be of limited use since the dams in Sala are situated so close to downstream buildings. Consequently warning and evacuation must take place before the dam failure is a fact, for instance for a significant leakage through the dam or for a significant water level increase in the reservoir. Here it is crucial that the right parameters are chosen for supervision.

4.3 Rise of dam crest

The Public building administration of Sala has suggested a 15 cm rise of the dam crest at Långforsen to level +65,95. The time before overtopping occurs is then increased by approximately 2 hours during the design flood.

The results from hydrological model runs, described in "Hydrologisk modellering av Sala Silvergruvas vattensystem" (Fridolf 2003), indicate that if a dam crest rise is used as the only risk reduction measure the design flood requires a dam crest rise of almost 2,5 m of Långforsen if the wind effect is also considered. And if Olov Jons and Silvköparen are considered as one reservoir a dam crest rise of almost 4 m including wind effects would be necessary at Olov Jons.

4.4 Increased spillway capacity

If the emergency spillway is fully used at Olov Jons the discharge capacity is raised from 4.5 to 6.3 m^3/s. The time before overtopping during a class I flood is then increased by about 30 minutes. Besides, this flow will cause flooding of summerhouses situated downstream. If the discharge capacity of Olov Jons is doubled from 4.5 to 9 m^3/s the time to overtopping is increased by about 1 hour.

A doubled discharge capacity of Långforsen from 4.5 to 9 m^3/s increases the time to overtopping by about 45 minutes.

4.5 Relocation of summer cottages

If it turns out to be practically and economically unjustified to upgrade the dams to safely pass a class I design flood, an alternative might be to move the summerhouses situated downstream Olov Jons dam and Långforsen in order to reduce the risk of lives being lost in case of dam failure.

4.6 Flood diversion

The Public building administration of Sala has suggested flood diversion as a way of increasing the dam safety. According to their suggestion flow diversions should be implemented at Storljusen, St Kråktjärn, Harsjöarna, Helgonmossdammen, Gräs-kärret and Svartsla, see figure 4.1.

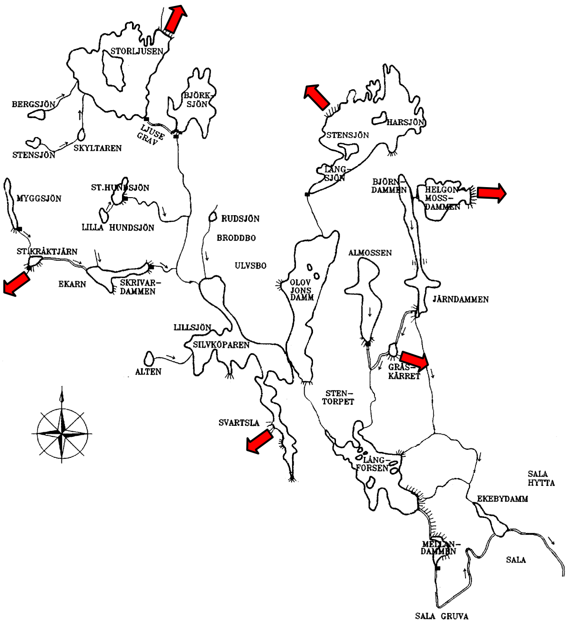

Figure 4.1 ***Suggested flood diversions in the water system***

According to the hydrological modelling of the system, the runoff from the areas in the north-eastern part, that is, around Harsjöarna and Helgonmossen does not contribute significantly to the design flood. Neither does the runoff from the area around Storljusen. It is therefore questionable if the indicated flood diversions from Storljusen, Harsjöarna, Helgonmossen and Gräskärret will have any significant impact on the dam safety.

According to the hydrological model run about 9 millions m^3 of water needs to be diverted at Svartsla during one month during a class I design flood in order to avoid overtopping of the dam crests. And during a 100-year rain about 1,5 millions m^3 needs to be diverted.

Possible risks with implementation of flood diversion:

- Flooding of the areas at Storljusen, St Kråktjärn, Harsjöarna, Helgonmoss-dammen, Gräskärret and Svartsla may lead to economical and environmental damages
- Construction measures at the dams may affect their value as historical monuments
- Construction measures at the dams may disturb them in a way that influence dam safety negatively. Lack of documentation increases the difficulty to predict the behaviour of the dams
- Implementation of flood diversions might complicate the water system and its regulation with an increased need for supervision

The areas to be flooded consist mainly of forests and mires. Consequently the economical and environmental damages to be expected are not very extensive. There are though some farms situated about 1 km downstream the planned outlet at Svartsla. And about 1,5 km downstream Helgonmossdammen there are also some farms to be considered. Besides there are in total about 15 to 20 summerhouses in the areas considered for flood diversion.

In order to keep necessary supervision and dependency on the human factor at a minimum the flood diversion should preferably be designed as a self-regulated system. It could consist of fuse plugs designed to be activated when a certain water level in the reservoir is exceeded or of ungated overflow spillways. The design however depends on the purpose of the flood diversion. Should diversion only occur during extreme floods or should also more modest flows like a 30- or 100-year flood be partly diverted? If diversion is considered necessary only during extreme floods the overflows could be designed as fuse plugs or ungated spillways. However if more modest and more frequently recurring floods should be diverted as well it may be desirable that the fuse plugs/ungated spillways are complemented with regulated discharge facilities. Consideration should also be taken to the historical value of the dams when designing the flood diversions.

4.7 Flood mitigation

The Public building administration in Sala has suggested that levees previously removed should be restored and new discharge facilities constructed at the smaller lakes/wetlands like Myggsjön and Almossen, to enable mitigation in the watershed. However, implementation of flood mitigation does not seem to have any significant mitigating effect on the extreme floods according to the results from the hydrological modelling.

5 RISK MANAGEMENT IN SALA

Considering the results from the risk assessment and risk reduction studies a reasonable risk management solution could be as described below. It is important to realise that risk management is a continual process that cannot be considered completed as long as the dams exist. It should be noted that focus in this study has been on the hydrological aspects of dam safety and that there is a need to evaluate the other risks posed to the dams as well.

5.1 Suggestion for risk management

Risk reduction measures for hydrological loads

To be prioritised:

- Construction of overflows at Svartsla and St. Kråktjärn in order to secure sufficient discharge capacity and avoid dam failure due to hydrological loads
- Installation of automatic water level measuring systems with alarm in Olov Jons dam and Långforsen
- Rise of the dam crests of Silvköparen, Olov Jons and Långforsen

Optional:

- Construction of overflows at Storljusen, Harsjöarna, Helgonmossen and Gräskärret
- Rise/restoration of dam crests of Storljusen, Harsjöarna and the small lakes/wetlands and installation of discharge facilities at the small lakes/wetlands
- Removal of summer houses situated immediately downstream Olov Jons and Långforsen

Risk reduction measures for other risks than hydrological loads

- Implementation of comprehensive dam safety evaluations with a suitable frequency
- Implementation of regular dam safety inspections by a dam inspector every third to fifth year
- Construction of a manual for operation, maintenance and supervision that should be continuously updated
- Construction of an emergency preparedness plan and an evacuation plan and information to the public
- Inspection of growing vegetation on the dams and removal of trees considered to pose a risk to the dam safety

6 CONCLUSIONS

6.1 Potential risk sources

The dams in Sala are exposed to different potential risk sources of which floods are one. Besides dam failure, floods are likely to cause other simultaneous problems at different places in the area making the situation even worse. Compared to the other risk sources a flood induced dam failure is likely to be preceded by a period of high flows giving some preparation time whereas a dam failure induced by internal erosion or uprooting trees are likely to come more as a surprise. During a flooding situation in Sala the possibility to observe a rise in water level at an early stage seems more crucial for the dam safety than the reliability of the discharge facilities.

6.2 Consequences and probability of a dam failure

In case of dam failure of Olov Jons or Långforsen about 10 to 30 lives would be at risk and the economical damages would probably amount to hundreds of millions SEK. Besides, an important monument of the Swedish industrial history would be seriously damaged.

The probability of dam failure in Sala can not be given as an absolute value due to the many uncertainties both considering the status of the dams and the loads on the dams. The results from the hydrological modelling indicate that the probability of dam failure one particular year, due to hydrological load could be as high as 1 in 100. The accumulated probability of dam failure due to hydrological load during a 100-year period would then amount to 63 %.

6.3 Tolerable risk level

An absolute value of tolerable risk is impossible to give. It can be concluded though that the requirement that Olov Jons and Långforsen should be able to safely handle a class I design flood is in line with present risk acceptance criteria abroad and that the risk posed by the dams today is unacceptable.

In Sala the determination of tolerable risk has to be a political decision. The politicians should consider the different possible scenarios and then based on available resources, costs for dam safety upgrading, historical/recreational value of the dams, moral aspects, public opinion etcetera make a decision. Preferably the citizens of Sala should be involved in the decision making process.

6.3 The applicability of the Swedish design flood guidelines

Nothing has been found that indicates that the Swedish guidelines for design flood should not be suitable in the Sala case due to the special features considering the historical value and age of the dams and the small scale of the water system. An overview of the Swedish guidelines is currently going on and one component deals with design flood criteria for dams with small watersheds.

6.4 Risk reduction measures

The risks in Sala can be reduced by:

- Diverting the floods
- Rising the dam crests
- Implementing regularly occurring dam safety inspections, comprehensive dam safety reviews and constructing a manual for operation, maintenance and supervision
- Introducing warning system, emergency preparedness plan and evacuation plan
- Relocating summerhouses
- Increasing the spillway capacity
- Implementing flood mitigation measures in the watershed

6.5 Proposed risk management strategy

Neither increasing the spillway capacity nor implementing flood mitigation measures in the watershed seem to have any significant effect on the dam safety in Sala. In order to safely handle the design flood and avoid dam failure due to overtopping it is necessary to divert the flood from the system.

Proposed risk management strategy for hydrological risks:

1. Construction of overflows at Svartsla and St. Kråktjärn
2. Installation of automatic water level measuring systems with alarm in Olov Jons dam and Långforsen
3. Rise of the dam crests of Silvköparen, Olov Jons and Långforsen

Though the focus in this study has been on the hydrological risks some obvious measures for reduction of other dam safety risks are also proposed:

- Regular dam inspections every third to fifth year and implementation of comprehensive dam safety evaluations
- Construction of a manual for operation, maintenance and supervision
- Construction of an emergency preparedness plan and an evacuation plan and information to the public
- Inspection of growing vegetation on the dams and removal of trees considered to pose a risk to the dam safety

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Hydrologisk modellering av

Sala silvergruvas vattensystem

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INNEHÅLLSFÖRTECKNING

SAMMANFATTNING

För att säkra tillgången till vattenkraft till Sala Silvergruva började man under 1500-talet att bygga ett omfattande vattensystem med dammar och kanaler. När Sala kommun övertog hela vattensystemet i början på 1990-talet upptäcktes att kraven på dammsäkerhet enligt Flödeskommitténs riktlinjer inte uppfylls. Sala kommun planerar därför att genomföra åtgärder för att säkerställa tillräcklig dammsäkerhet.

Ett led i detta arbete har varit att utveckla en hydrologisk modell över området för att få en uppfattning om hur flödesbilden ser ut och vilka effekterna blir av olika planerade åtgärder i vattensystemet.

Den modell som valts är HEC-HMS (Hydrologic Engineering Center - Hydrologic Modeling System) som är utvecklad av US Army Corps of Engineers.

Den hydrologiska modellen över området har kalibrerats för en regnstorm under november 2000. SMHI har uppskattat återkomsttiden för flödet under denna period till 25 år. Validering av modellen har gjorts mot en liknande situation under april 1999.

Den framkalibrerade modellen har körts dels med en dimensionerande regnsekvens enligt Flödeskommitténs riktlinjer, dels med regnsekvenser med återkomsttid 5-, 10-, 30- respektive 100 år framtagna med hjälp av frekvensanalys. Modellen har sedan modifierats för att simulera situationen efter införandet av de av Sala kommun planerade framtida flödesdämpande åtgärderna.

Tabell A visar resulterande högsta vattenstånd när modellen körs med befintliga förhållanden.

Tabell A ***Resulterande högsta vattenstånd med befintliga förhållanden och antagen innehållen översvämning. "Silvk + Olov J" avser förhållandena om Silvköparen och Olov Jons räknas som ett sammanhängande magasin.***

RESERVOAR	DAMM-KRÖN	KLASS I REGN	100-ÅRS REGN	30-ÅRS REGN	10-ÅRS REGN	5-ÅRS REGN
Storljusen	+92.10	+92.89	+92.05	+91.98	+91.91	+91.86
Harsjöarna	+81.50	+83.55	+81.78	+81.64	+81.51	+81.44
Silvköparen	+72.30	+76.71	+73.18	+72.86	+72.55	+72.33
Olov Jons	+72.60	+73.32	+72.27	+72.19	+72.10	+72.07
Silvk + Olov J	-	+75.61	+72.84	+72.60	+72.41	+72.29
Långforsen	+65.80	+67.23	+65.79	+65.76	+65.63	+65.54

1 INLEDNING

1.1 Bakgrund

I samband med gruvbrytningen i Sala silvergruva ställdes stora krav på tillgång till vattenkraft. Inom området fanns dock inga stora naturliga höjdskillnader eller något större naturligt vattendrag som kunde utnyttjas. Med början på 1500-talet byggdes därför ett omfattande vattensystem med dammvallar, kanaler och regleringar upp kring Sala silvergruva. Utbyggnaden skedde i tre etapper:

- 1509-1543 anlades Långforsen, Olovjons damm och Silvköparen,
- 1595-1660 anlades Skrivardammsystemet, Hundsjöarna, Storljusen, Björksjön och Harsjöarna,
- 1819-1822 byggdes Järndammsystemet.

Därmed kunde man samla in vattnet från många små sjöar inom ett cirka 100 km^2 stort område och säkra gruvans behov av vattenkraft. Dessa vattenutbyggnader var ett av Sveriges största ingenjörsföretag under 1500- och 1600-talen.

Gruvbrytningen vid silvergruvan lades ner 1908 och därmed försvann också behovet av vattenkraft, och underhållet av vattensystemet eftersattes under en lång tid. När Sala kommun tog över systemet 1989, upptäcktes att dammsäkerheten inte var tillfredsställande enligt de nya riktlinjerna för bestämning av dimensionerande flöden för dammanläggningar som utformats av Flödeskommittén.

De äldsta dammarna i systemet är från början av 1500-talet och kulturminnesmärkta vilket medför att inga omfattande ombyggnader får utföras. Dessutom har vattensystemet ett stort bruksvärde som rekreationsområde för Salaborna.

Alternativa dammsäkerhetshöjande åtgärder, som till exempel omledning av flöden, behöver därför utvärderas, vilket i sin tur kräver att man kan beskriva flödessituationen i området.

En tidigare studie av flödessituationen för vattensystemet i Sala utfördes 1994 av SMHI (Olofsson et al. 1994). I studien beräknades dimensionerande flöden och vattenstånd för vattensystemet enligt Flödeskommitténs riktlinjer med hjälp av HBV modellen. I samband med studien utfördes också en klassificering av dammarna, där Olof Jons damm och Långforsen klassades som klass I dammar. Det dimensionerande tillfället enligt SMHIs modellering inträffar i augusti 1987 och de resulterande vattennivåerna överskrider dammkrönet vid Storljusen med drygt 0.5 m och dammkrönen vid Stensjön, Silvköparen / Olov Jons damm och Långforsen med drygt 1 m. Modellen kördes också med ett regn som utgjorde 70 % av det dimensionerande regnet. De resulterande vattennivåerna vid Silvköparen / Olov Jons och Långforsen sjunker då till drygt 0.1 m över dammkrön. Eftersom inga uppmätta flöden i det aktuella avrinningsområdet fanns tillgängliga vid studiens genomförande, kalibrerades modellen mot uppmätta, oreglerade flöden i omkringliggande områden. Resultaten sågs därför som osäkra och för att förbättra kunskaperna om vattensystemets hydrologi beslöts att starta flödesmätningar vid ett antal platser i området och därefter utföra en ny hydrologisk modellering baserad på dessa nya data.

1.2 Syfte

Syftet med denna studie har varit att:

- utveckla en hydrologisk modell över vattensystemet för att kunna beskriva flödessituationen i området
- använda tillgängliga data på nederbörd och uppmätt vattenföring för att kalibrera och validera modellen
- köra modellen med det dimensionerande regn enligt Flödeskommitténs riktlinjer som tidigare tagits fram av SMHI

- köra modellen med framtagna regnsekvenser med återkomsttid 5-, 10-, 30-, och 100 år
- modifiera och köra modellen enligt Sala kommuns planerade flödesdämpnings-åtgärder för att kunna utvärdera effekten av åtgärderna

Den framtagna modellen ska kontinuerligt kunna användas som underlag av Sala kommun vid beslut om lämpliga åtgärder för att öka dammsäkerheten i området.

2 FÖRUTSÄTTNINGAR OCH ANTAGANDEN

En fullständig modellering strikt enligt Flödeskommitténs riktlinjer har inte utförts. I stället har resultat från den modellering av vattensystemet som utfördes av SMHI 1994 använts som underlag (Olofsson et al. 1994). Som input i den hydrologiska modellen har använts det dimensionerande regntillfälle som gavs av SMHI studien, det vill säga augusti 1987. Därmed har inte någon hänsyn tagits till snösmältning i modellen.

Vid modelleringen har antagits att dammarna kan motstå överströmning utan dammbrott. Dessutom har antagits att kanaler och diken som sammanbinder sjöarna har tillräcklig hydraulisk kapacitet.

Den hydrologiska analysen reproducerar inte verkligheten exakt och det finns osäkerheter och slumpmässiga variationer i hur avrinning sker. Resultaten av modelleringen ska därför ses i första hand som en vägledning till insikt om möjliga flödesscenarier i området.

3 TILLGÄNGLIGA DATA

Tillförlitligheten och användbarheten av en hydrologisk modell är beroende av tillgång och kvalitet på data för det aktuella avrinningsområdet.

Nedan följer en lista på de data som varit tillgängliga vid upprättandet av den hydrologiska modellen för Sala.

- Dagliga nederbördsvärden från SMHIs mätare 9655 , belägen i Öja, ca 3 km sydöst om Sala från perioden 1961-2000
- Uppmätt flöde för perioden 001001-010228 för Storljusen, Långsjön, OlovJons och Långforsen
- Uppmätt flöde för perioden 990324-990508 för Storljusen, Långsjön, OlovJons och Långforsen
- Enstaka värden på uppmätt flöde vid samtliga mätpunkter (19 st.) i systemet för perioden 971113-990427
- Area/volym förhållande för Storljusen, Harsjöarna, OlovJons, Silvköparen samt Långforsen
- Kurva över förhållandet mellan sjönivå i Storljusen och läckage genom dammvallarna i norr. För de övriga sjöarna finns uppskattningar av läckagets storlek genom dammvallarna.
- Uppskattning av dikesbredder och flödeshastigheter i kanaler och diken
- Uppskattning av rinntider i kanaler och diken
- Uppmätningsritningar över utrivna fördämningar
- Terrängmodell över Björksjön, Myggsjön, St. Kråktjärn, Skrivardammen, Hundsjön, Helgonmossdammen, Björndammen, Järndammen, Gräskärret och Almossen
- SGUs jordartskarta för närliggande område
- Topografiska kartan över området i skala 1:50 000 (11G NO Västerås samt 12G SO Avesta).
- Gula kartan över området i skala 1:20 000 (11G:85, 11G:88 samt 12G:06)
- Tappningstabell för regleringssjöarna
- Föreslagna åtgärder för flödesdämpning i området

Jordartsdata

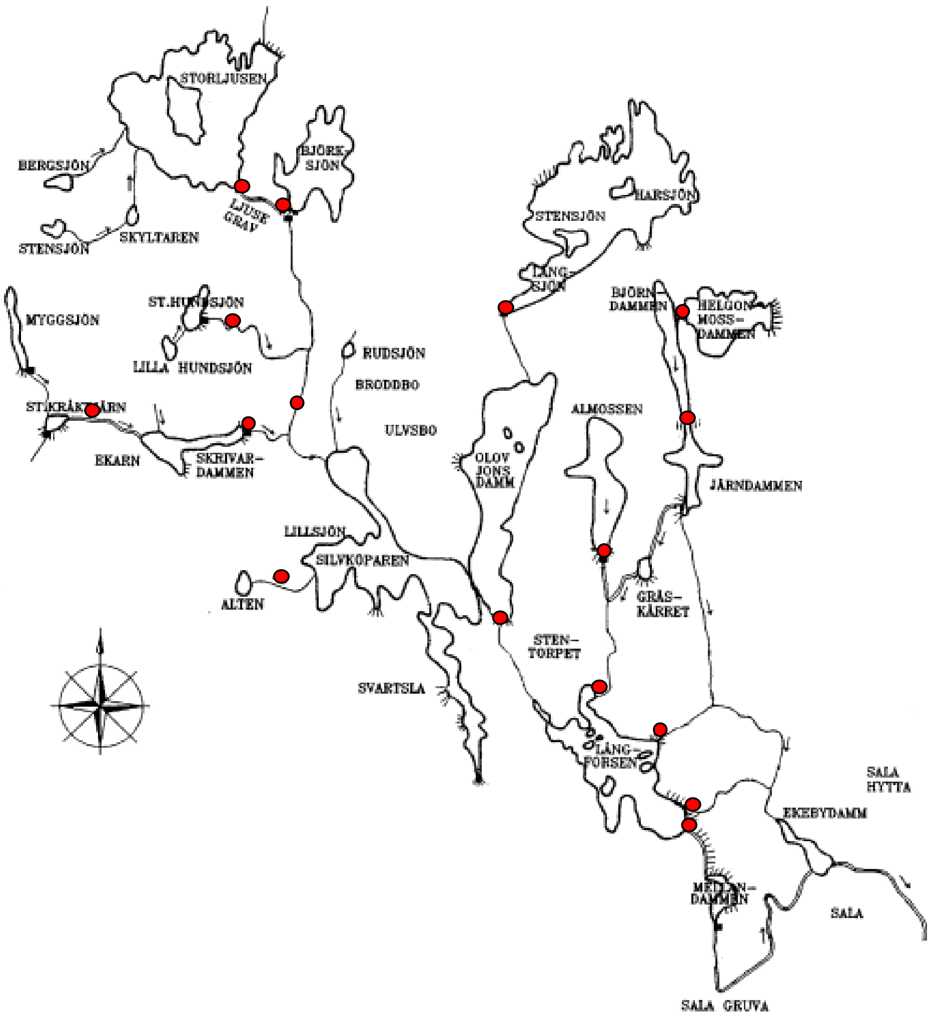
De hydrologiska egenskaperna är knutna till jordarter och markanvändning varför en jordartskarta är till hjälp vid uppskattningen av ett områdes hydrologiska egenskaper. För avrinningsområdet i Sala finns dock ingen jordartskarta upprättad. En uppskattning av jordartsfördelningen har därför fått göras med hjälp av SGUs jordartskarta för området söder om det aktuella avrinningsområdet.

Nederbördsdata

Dygnsnederbördsvärden från SMHIs mätare 9655 har använts vid kalibrering och validering av modellen.

Flödesdata

Sala kommun har mätt upp flöden vid ett antal platser i avrinningsområdet. Mätpunkternas läge är utmärkta i figur 3.1. Mätning av vattenföring har endast gjorts i samband med reglering av sjösystemet varför en kontinuerlig mätserie inte erhållits. Följaktligen kan mätningarna ha missat vissa flödestoppar. Enligt Sala kommun har det dock inte hänt så mycket med flödet mellan mättillfällena så troligtvis har man inte missat så många flödestoppar. För Storljusen, Långsjön, OlovJons och Långforsen finns flödesdata registrerade från och med 1996 och från 1999 har daglig registrering skett via ett fjärravläsningssystem.



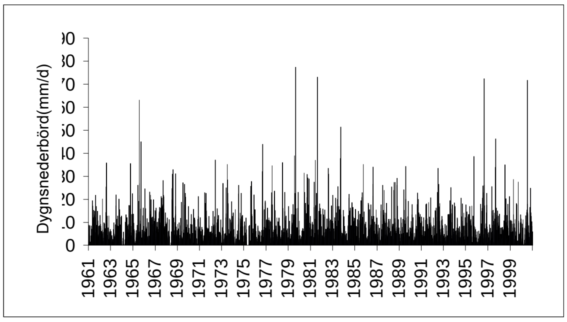
Figur 3.1 ***Mätpunkternas läge markerade som punkter***

4 NEDERBÖRDSANALYS

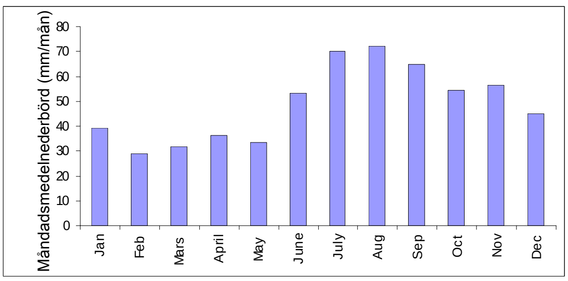
En dimensionerande regnsekvens enligt Flödeskommitténs riktlinjer för bestämning av dimensionerande flöde resulterar i en mycket omfattande översvämningssituation i Sala. Det kan ifrågasättas om det är rimligt att kräva att systemet på ett säkert sätt ska kunna hantera ett klass I-flöde. För att kunna göra en indirekt uppskattning av sannolikheten för översvämning beslöts att ta fram regn med olika återkomsttid och sedan köra den hydrologiska modellen med dessa regn och utvärdera resulterande flöden. Frekvensanalys har använts för att ta fram regnsekvenserna.

4.1 Data

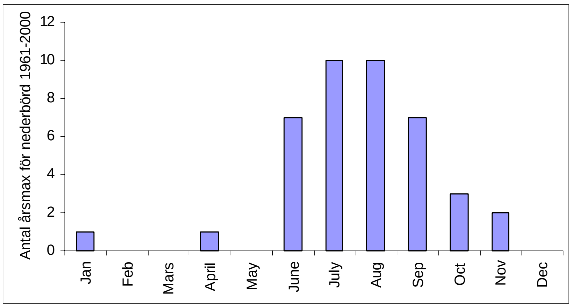
Dygnsnederbördsvärden för perioden 1961-01-01 till 2000-12-31 från SMHIs station 9655 som är placerad ca 3 km sydöst om Sala centrum, har använts.



Figur 4.1 ***Dygnsnederbörd i Sala 1961-2000***



Figur 4.2 ***Månadsmedelnederbörd i Sala 1961-2000***



Figur 4.3 ***Antal årliga dygnsmaxvärden på nederbörd varje månad under perioden 1961-2000***

Den högsta uppmätta dygnsnederbörden under perioden är 77.5 mm som inträffade den 26 augusti 1979. Diagrammen i figur 4.2 och 4.3 visar att augusti har den högsta månadsmedelnederbörden och tillsammans med juli också den högsta frekvensen av årliga maxvärden. Även juni och september har hög frekvens årliga maxvärden.

81 % av de årliga maxvärdena för dygnsnederbörd ligger i intervallet 21-40 mm/dygn.

4.2 Frekvensanalys

Frekvensanalys har använts för att bestämma nederbörd med olika återkomsttid. Sannolikhetsfördelningarna som använts vid frekvensanalysen är Gumbel-, Lognormal- och Log-Pearson Typ III-fördelning. Frekvensanalysen baseras på årliga maxvärden. Det finns ingen generell enighet mellan hydrologer om vilken sannolikhetsfördelning som är bäst lämpad att beskriva höga flöden (Kite 1988).

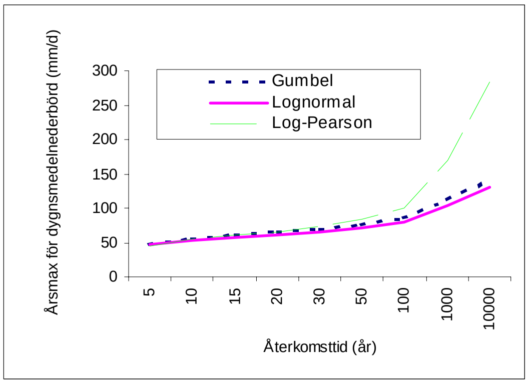
Gumbelfördelningar har använts mycket inom hydrologin. De utgör basen för den standardiserade metoden för frekvensanalys av flöden i Storbritannien (Chow et al. 1988).

Log-Pearson Typ III är standard-fördelningen för frekvensanalys av årliga maximala flöden i USA. Fördelningen har visat sig ge goda resultat i många tillämpningar särskilt för extrema flöden (Chow et al. 1988).

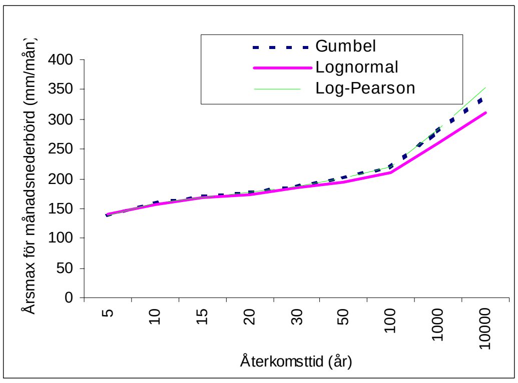
4.2.1 Resultat från frekvensanalysen

Tabell 4.1 ***Beräknade årsmax av dygnsnederbörd för olika återkomsttider.***

ÅTER-KOMST-TID (år)	ÅRLIGT MAX (mm/d) GUMBEL	90% KONFI-DENS INTER-VALL	ÅRLIGT MAX (mm/d) LOGNORMAL	90% KONFI-DENS INTER-VALL	ÅRLIGT MAX (mm/d) LOG-PEARSON TYP III	90% KONFI-DENS INTER-VALL
5	47	41 – 54	46	40 - 51	44	42 – 47
10	56	48 - 65	54	47 - 60	55	50 – 59
15	62	52 – 71	58	51 – 65	61	
20	65	54 – 76	61	54 - 69	66	59 – 74
30	70	58 – 82	66	58 – 74	74	
50	76	63 – 90	71	63 – 80	84	70 – 98
100	85	69 – 101	79	69 – 88	100	79 - 120
1 000	112	89 – 136	104	92 – 116	170	
10 000	140	109 - 171	131	118 - 145	284	
2000-07-19	72 mm					



Figur 4.4 ***Årsmax av dygnsnederbörd med olika sannolikhetsfördelningar.***



Figur 4.5 ***Årsmax av månadsnederbörd med olika sannolikhetsfördelningar.***

Årsmaxvärdena för de olika sannolikhetsfördelningarna överensstämmer relativt bra upp till återkomsttider på 50 till 100 år för såväl dygnsnederbörd som månadsnederbörd. För dygnsnederbördens årsmax stämmer värdena för Gumbel och Lognormal fortfarande relativt bra för återkomsttider överstigande 100 år, medan kurvan för Log-Pearson Typ III fördelningen avviker betydligt. För månadsnederbörden överensstämmer kurvorna för Gumbel och Log-Pearson Typ III bra även för återkomsttider över 100 år medan Lognormal kurvan avviker något.

Eftersom tillgängliga data på uppmätt nederbörd bara sträcker sig över 40 år är det inte heller rimligt att förvänta sig tillförlitliga värden på nederbörd med så långa återkomsttider som 1 000 till 10 000 år. En tumregel är att återkomsttider som överstiger dubbla observationsperioden inte är tillförlitliga (Killingtveit et al. 1995).

4.2.2 Val av nederbördssekvens

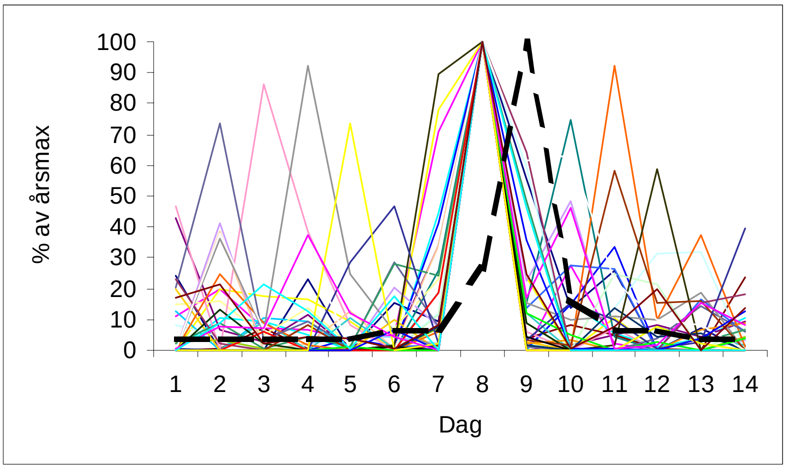
Enligt Flödeskommitténs riktlinjer ska vid bestämning av klass I-flöde en 14-dagars regnsekvens användas. Dimensionerande regnsekvens för beräkning av klass I-flöde i Sala visas i tabell 4.2. Sekvensen är tagen från SMHIs studie från 1994 (Olofsson et al. 1994) och inkluderar korrektion för avrinningsområdets area. Flödeskommitténs grundsekvens för dimensionerande regn är baserad på regn över ett område på 1000 km^2 (Flödeskommittén 1990). Beroende på storleken på det aktuella avrinningsområdet justeras sedan denna grundsekvens.

Tabell 4.2 ***Dimensionerande regnsekvens i Sala enligt Flödeskommitténs riktlinjer för bestämning av dimensionerande flöde för klass I dammar***

Dag	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**
Regn (mm/d)	8	8	8	8	8	13	13	51	191	32	13	13	8	8
% av dag 9	4	4	4	4	4	7	7	27	100	17	7	7	4	4

Av förenklingsskäl har en 14-dagars sekvens använts för samtliga återkomsttider.

De 14-dagars regnsekvenser som omger det årliga maxvärdet för dygnsnederbörd under perioden 1961-2000 har ritats in i figur 4.6. Det framgår att skillnaderna mellan fördelningarna för olika år är stora och ingen typisk 14-dagars sekvens kan utläsas.



Figur 4.6 ***Nederbördsvärden kring årsmax (dag 9) 1961-2000. Den streckade kurvan visar fördelningen enligt Flödeskommitténs riktlinjer.***

Eftersom ingen typisk 14-dagars fördelning kan utläsas har samma fördelning som för dimensionerande regn enligt Flödes-kommittén använts för bestämning av 14-dagars regnsekvenser med olika återkomsttid.

Tabell 4.3 **14-dagars regn. Fördelningsfunktion: Gumbel**

Dag	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Återkomsttid														
5	2	2	2	2	2	3	3	13	47	8	3	3	2	2
10	2	2	2	2	2	4	4	15	56	10	4	4	2	2
15	2	2	2	2	2	4	4	17	62	11	4	4	2	2
20	3	3	3	3	3	5	5	18	65	11	5	5	3	3
30	3	3	3	3	3	5	5	19	70	12	5	5	3	3
50	3	3	3	3	3	5	5	21	76	13	5	5	3	3
100	3	3	3	3	3	6	6	23	85	14	6	6	3	3
1 000	4	4	4	4	4	8	8	30	112	19	8	8	4	4
10 000	6	6	6	6	6	10	10	38	140	24	10	10	6	6

Tabell 4.4 **14-dagars regn. Fördelningsfunktion: Lognormal**

Dag	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Återkomsttid														
5	2	2	2	2	2	3	3	12	46	8	3	3	2	2
10	2	2	2	2	2	4	4	15	54	9	4	4	2	2
15	2	2	2	2	2	4	4	16	58	10	4	4	2	2
20	2	2	2	2	2	4	4	16	61	10	4	4	2	2
30	3	3	3	3	3	5	5	18	66	11	5	5	3	3
50	3	3	3	3	3	5	5	19	71	12	5	5	3	3
100	3	3	3	3	3	6	6	21	79	13	6	6	3	3
1 000	4	4	4	4	4	7	7	28	104	18	7	7	4	4
10 000	5	5	5	5	5	9	9	35	131	22	9	9	5	5

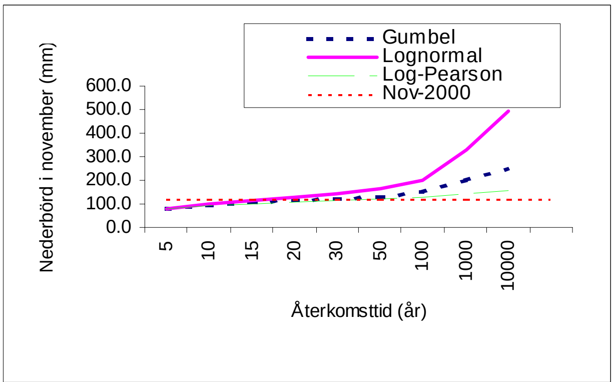
Tabell 4.5 **14-dagars regn. Fördelningsfunktion: Log-Pearson Typ III**

Dag	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Återkomsttid														
5	2	2	2	2	2	3	3	12	44	8	3	3	2	2
10	2	2	2	2	2	4	4	15	55	9	4	4	2	2
15	2	2	2	2	2	4	4	16	61	10	4	4	2	2
20	3	3	3	3	3	5	5	18	66	11	5	5	3	3
30	3	3	3	3	3	5	5	20	74	13	5	5	3	3
50	3	3	3	3	3	6	6	23	84	14	6	6	3	3
100	4	4	4	4	4	7	7	27	100	17	7	7	4	4
1 000	7	7	7	7	7	12	12	46	170	29	12	12	7	7
10 000	11	11	11	11	11	20	20	77	284	48	20	20	11	11

4.3 Jämförelse med regnen i juli och november 2000

I juli 2000 föll den högst uppmätta nederbörden någonsin på en del platser i Sverige. De områden som påverkades mest var södra Norrland, inre Svealand och nordöstra Götaland.

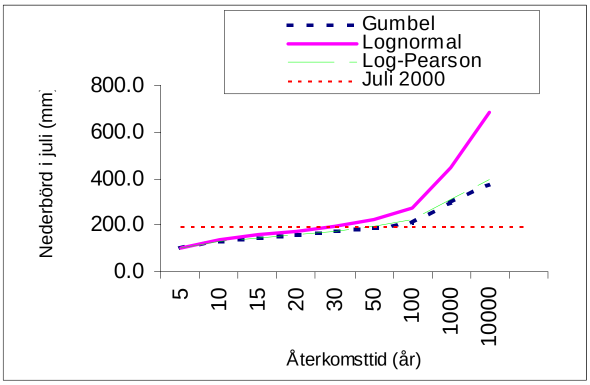
En jämförelse har gjorts med dagliga nederbördsdata från juli 2000. Figur 4.7 visar resultaten från frekvensanalys för månadsnederbörd för juli 1961-2000. Regnet i juli 2000 har en återkomsttid på 31 till 64 år beroende på vilken fördelningsfunktion som används. Om jämförelsen istället görs för månadsnederbörd över hela året blir återkomsttiden för regnet i juli ungefär 10 år.



Figur 4.7 ***Månadsnederbörd i juli***

På eftermiddagen den 19 juli 2000 fick Sala 72 mm under en åskskur. Värdet har bara överskridits tre gånger under mätperioden: 1979-08-26: 77.5 mm, 1981-08-16: 73 mm och 1996-08-25: 72.5 mm.

Hög nederbörd inträffade också i november 2000. Resultaten från frekvensanalys för nederbörden i november 1961-2000 visas i figur 4.8. Novemberregnet 2000 har en återkomsttid på 18 till 88 år beroende på vilken fördelningsfunktion som används. Om jämförelsen istället görs med månadsnederbörd över hela året blir återkomsttiden för novemberregnet 2000 bara 2 till 3 år. Följaktligen var nederbörden mycket hög för årstiden med inte jämfört med nederbörden över hela året.



Figur 4.8 ***Månadsnederbörd i november***

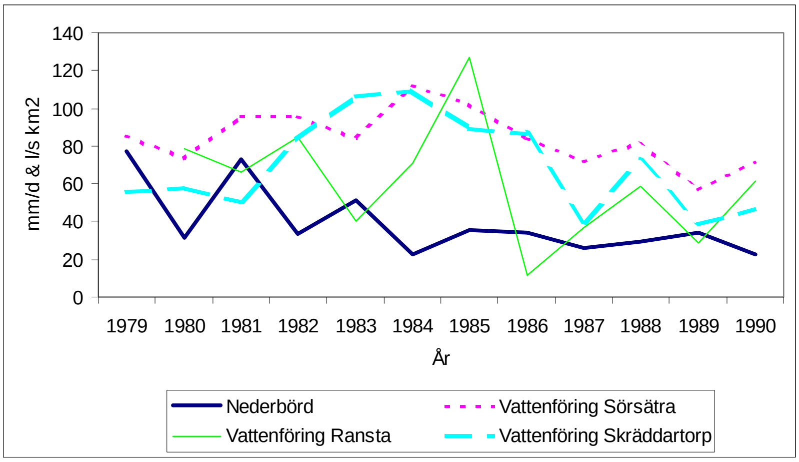
4.4 Jämförelse med dimensionerade regn enligt Flödeskommitténs riktlinjer

I beräkningarna av klass I-flödet för Långforsen och Olov Jons damm är det högsta värdet i den dimensionerande regnsekvensen 191 mm. Som jämförelse ger resultaten från frekvensanalysen enligt tabell 4.1 att ett 10 000 års regn varierar mellan 131 och 284 mm beroende på vilken fördelningsfunktion som används. Som tidigare nämnts är en tumregel att återkomsttider som överskrider dubbla observationsperioden inte är tillförlitliga. Jämförelsen ovan ska följaktligen tolkas med stor försiktighet och ses som ett exempel på svårigheterna att bestämma sannolikheterna för extrema regn.

4.5 Jämförelse med uppmätta flöden

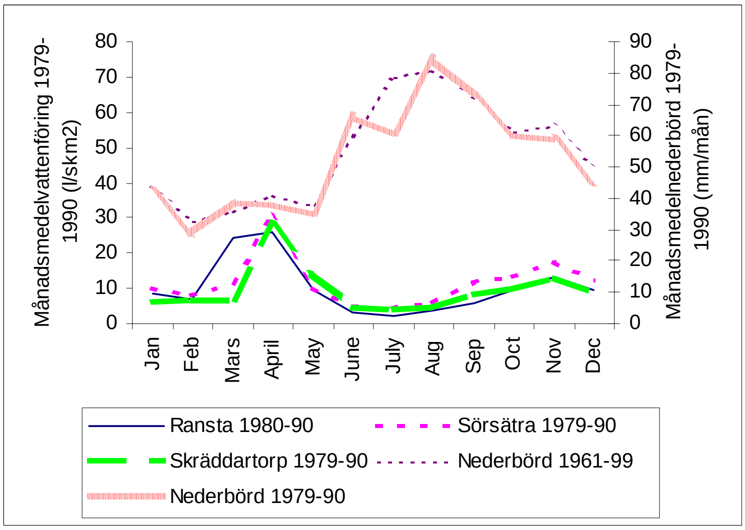
Det är svårt att bestämma återkomsttiden för höga flöden med hjälp av återkomsttiden för regn. Det är sällan att de mest extrema flödena orsakas av extrema regn (Lindström et al. 1993). Istället orsakas ofta extrema flöden av snösmältning eller regn med lång varaktighet eller en kombination av olika faktorer.

En annan svårighet i Sala är att långa kontinuerliga mätserier av flödesdata från vattensystemet saknas. Däremot existerar flödesdata för de närliggande stationerna Sörsätra, Ransta och Skräddartorp för perioden 1979-1990 (SMHI 1993). I figur 4.9 är årlig maximal nederbörd inritad i samma diagram som vattenföringens årsmax vid Sörsätra, Ransta och Skräddartorp.



Figur 4.9 ***Nederbörd och vattenföring – årliga maxvärden, 1979-1990***

Figur 4.9 visar inget direkt samband mellan nederbörd och vattenföring.



Figur 4.10 ***Nederbörd och vattenföring – månadsmedelvärden under perioden 1979-1990***

Nederbördens variation över året skiljer sig från vattenföringens enligt figur 4.10. Den högsta månadsmedelnederbörden inträffar under sommarmånaderna medan månadsmedelvattenföringen istället är högst i april och lägst under sommarmånaderna.

Skillnaderna i årsvariation mellan nederbörd och vattenföring kan ha olika orsaker:

- Under sommaren är evapotranspirationen högre än under vintern på grund av högre temperatur och tätare vegetation.
- Snösmältning förekommer under våren.
- Markfuktighetsunderskottet är sannolikt högre under sommaren än under våren.

4.6 Felkällor

Möjliga felkällor kopplade till bestämningen av regn med olika återkomsttid är:

- Mätfel
- Val av sannolikhetsfördelning
- Användningen av årliga maxvärden betyder att värden som understiger årsmax ett år kan överstiga årsmax ett annat år. Om å andra sidan alla värden överskridande ett visst gränsvärde används finns en risk för beroende mellan värdena.
- Framtida förändringar som en förändring av klimatet eller förändrad markanvändning. Principen för frekvensanalys är baserad på användningen av historiska data för att förutsäga framtiden. En förutsättning är dock att de förhållanden som rådde då data uppmättes inte förändras i framtiden.
- Dygnsmedelvärden på nederbörd har använts. Eftersom avrinningsområdet i Sala är litet kan dock regn med kortare varaktighet påverka avrinningsmönstret. Resultatet kunde tillexempel ha blivit annorlunda om 3-timmars regn använts istället.

4.7 Slutsatser

Det högsta dygnsmedelvärdet på nederbörd under perioden är 77.5 mm och inträffade den 26 augusti 1979. Sommarmånaderna tillsammans med september har högst frekvens av årliga maxvärden.

Beroende på vilken sannolikhetsfördelning som används varierar 10-års regnet mellan 54 och 56 mm/d. Motsvarande värde för 30-års regn och 100-års regn är 66-74 mm/d och 79-100 mm/d.

En jämförelse görs mellan månadsmedelvärden för juli 1961-2000 och juliregnet 2000. Beroende på vilken sannolikhetsfördelning som väljs har regnet som inträffade i juli 2000 en återkomsttid på 31 till 64 år. En motsvarande jämförelse har gjorts för novemberregnet 2000 som beroende på sannolikhetsfördelning har en återkomsttid på 18 till 88 år.

En jämförelse har även gjorts med regnet som ska användas för bestämning av dimensionerande klass-I flöde enligt Flödeskommitténs riktlinjer. Det högsta värdet i den dimensionerande 14 dagars sekvensen överstiger 10,000 års regnet beräknat med Gumbel- och Lognormalfördelningen men understiger 10,000 års regnet beräknat med Log-Pearson Typ III fördelningen.

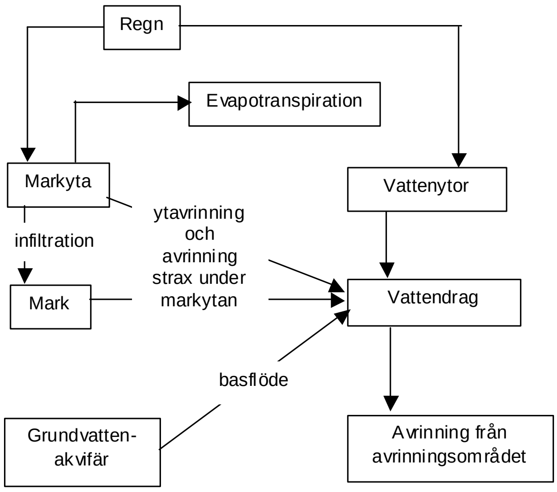
Uppmätt vattenföring vid tre närliggande stationer, Sörsätra, Ransta och Skräddartorp har jämförts med nederbörden i Sala. Ingen korrelation mellan årlig maximal nederbörd och vattenföring kan ses. Dessutom skiljer sig nederbördens årsvariation mot vattenföringens årsvariation. Den högsta månadsmedelnederbörden inträffar under sommaren medan månadsmedel-vattenföringen är högst i april och lägst under sommaren.

Resultaten för Log-Pearson fördelningen avviker från de två övriga sannolikhetsfördelningarna enligt figur 4.4 och ger en återkomsttid på 88 år för novemberregnet 2000 vilket bedöms som orimligt högt. Baserat på detta har valts att köra den hydrologiska modellen endast med regn framtagna med Gumbel- respektive Lognormal fördelning.

5 DEN HYDROLOGISKA MODELLEN

Den hydrologiska datormodell som använts för simulering av avrinning i Sala är HEC-HMS (Hydrologic Engineering Center-Hydrologic Modeling System). Modellen är utvecklad av US Army Corps of Engineers och är en vidareutveckling av HEC-1 modellen. HEC-HMS kan hämtas kostnadsfritt från: *http://www.wrc-hec.usace.army.mil/software/software_distrib/hec-hms/hechmsprogram.html.*

HEC-HMS innehåller olika hydrologiska beräkningsmodeller för simulering av regn- och avrinningsprocesser. Figur 5.1 visar principiellt hur avrinning beskrivs i HEC-HMS.



Figur 5.1 ***Principskiss över hur avrinning från ett avrinningsområde beskrivs i HEC-HMS***

För simulering av regn-/avrinningsprocesser innehåller HEC-HMS modeller för:

- beräkning av effektiv nederbörd,
- beräkning av direkt avrinning,
- beräkning av basflöde samt
- beräkning av flödesutjämning i vattendrag.

Valet av beräkningsmetoder baseras bl.a. på syftet med den hydrologiska modelleringen, hur pass väl kända egenskaperna hos avrinningsområdet är och tillgången på mätdata för kalibrering. De tillgängliga beräkningsmodellerna i HEC-HMS är förtecknade i tabell 5.1.

För modellerna i tabell 5.1 gäller att:

- De flesta är händelsemodeller dvs. de simulerar ett enskilt regn till skillnad från kontinuerliga modeller som simulerar en längre period.
- Med undantag av ModClark är modellerna icke-distribuerade dvs. de tar inte hänsyn till rumsliga variationer.
- Det ingår både empiriska och konceptuella modeller. Konceptuella modeller baseras på kunskap om de bakomliggande fysiska processerna medan empiriska modeller baseras på observationer.
- Alla modellerna i HEC-HMS är deterministiska dvs. indata, parametrar och processer i modellerna anses fria från slumpmässiga variationer och kända med säkerhet.

Nedan följer en beskrivning av de beräkningsmetoder som valts för modellering av vattensystemet i Sala. För beskrivning av de andra beräknings-metoderna hänvisas till användarmanualen för HEC-HMS (US Army Corps of Engineers 2001).

Tabell 5.1 ***Tillgängliga beräkningsmodeller i HEC-HMS för beräkning av effektiv nederbörd, direkt avrinning, basflöde och flödesutjämning i vattendrag***

EFFEKTIV NEDERBÖRD	DIREKT AVRINNING	BASFLÖDE	UTJÄMNING I VATTENDRAG
Initial and constant rate	User specified unit hydrograph, UH	Constant, monthly	Lag
SCS curve number, CN	Clark´s UH	Exponential recession	Muskingum
Gridded SCS CN	Snyder´s UH	Linear reservoir	Modified Puls
Green and Ampt	SCS UH		Kinematic wave
Deficit and constant rate	ModClark		Muskingum Cunge
Soil moisture accounting, SMA	Kinematic wave		
Gridded SMA			

5.1 Beräkning av effektiv nederbörd

Effektiv nederbörd är den delen av nederbörden som bidrar till direkt avrinning och beräknas genom att från nederbörden dra ifrån förluster i form interception, infiltration, ytmagasinering, avdunstning och transpiration. Den modell som använts för avrinningsområdet i Sala är ”Deficit and constant loss rate”. En initiell magasineringskapacitet för markfuktighet anges. Denna magasineringskapacitet måste vara uppnådd innan effektiv nederbörd kan uppstå. Den intiella magasinerings-kapaciteten, I_a, beskriver interception och magasinering i sänkor i markytan. Om avrinningsområdet är mättat närmar sig I_a noll. När väl magasineringskapaciteten är fylld sker förluster med en definierad konstant hastighet, f_c, som kan betraktas som infiltrationskapaciteten hos marken.

$$pe_t = \begin{cases} 0 & \text{om} \sum p_i < I_a \\ p_t - f_c & \text{om} \sum p_i > I_a \text{ och } p_t > f_c \\ 0 & \text{om} \sum p_i > I_a \text{ och } p_t < f_c \end{cases}$$

pe_t = effektiv nederbörd vid tiden t

p_t = nederbörd vid tiden t

f_c = konstant förlusthastighet

I_a = Initiell magasineringskapacitet

Magasineringskapaciteten kan återhämta sig efter en längre period utan regn. HEC-HMS beräknar kontinuerligt markfuktighets-underskottet som det initiella mark-fuktighetsunderskottet minus nederbörds-volym plus återhämtningsvolym under regnfria perioder.

De parametrar som anges i modellen är initiell magasineringskapacitet, maximal magasineringskapacitet, förlusthastighet och återhämtningshastighet samt andel hård-gjorda ytor.

5.2 Modellering av direkt avrinning

För omvandling av effektiv nederbörd till direkt avrinning har Snyders enhets-hydrograf använts. Enhetshydrografen är avrinningen som funktion av tiden för ett regn med viss varaktighet och med enhetsintensitet (vanligast 1 mm över varaktigheten). Regn med olika varaktighet har olika enhetshydrografer (Bengtsson 1994). Teorin för enhetshydrograf baseras på antagandet att ett område alltid reagerar på samma sätt då en given mängd nederbörd tillförs ett område och att avrinningen i varje ögonblick är proportionell mot regnet i ett tidigare ögonblick. Avrinningen till följd av ett regn med en viss varaktighet pågår oavsett regnets intensitet över en tidsperiod med given längd. HEC-HMS använder en diskret beskrivning av effektiv nederbörd, där en puls av effektiv nederbörd är känd för varje tidsintervall.

$$Q_n = \sum_{m=1}^{n \le M} P_m U_{n-m+1}$$

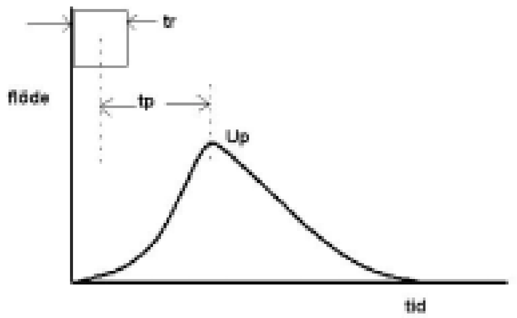
Q_n = Värdet på hydrografen vid tiden $n\Delta t$

P_m = effektiv nederbörd under tidsintervallet $m\Delta t$ till $(m+1)\Delta t$

M = totalt antal diskreta regnpulser

U_{n-m+1} = enhetshydrografvärdet vid tiden $(n-m+1)\Delta t$

Snyder definierade en standardenhets-hydrograf som en vars regnintensitet, t_r, relateras till avrinningsområdets fördröjning, t_p, som $t_p = 5{,}5t_r$



Figur 5.2 ***Snyders enhetshydrograf***

$$\frac{U_p}{A} = C_2 \frac{C_p}{t_p}$$

U_p = toppvärde hos standardenhetshydrografen

A = avrinningsområdets area

C_p = koefficient

C_2 = konstant = 2,75

t_p kan uppskattas som

$t_p = C_1 C_t (LL_c)^{0,3}$

C_t = avrinningsområdeskoefficient (kalibreras fram)

L = längd på huvudvattendraget från utflödet till uppströms vattendelare

L_c = avstånd från utflödet till en punkt längs vattendraget närmast avrinningsområdets mittpunkt

C_1 = konstant = 0,75

5.3 Modellering av basflöde

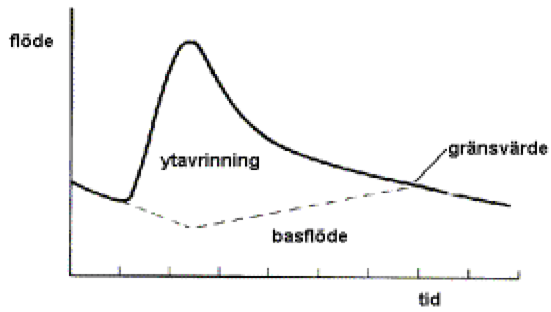
Basflödet utgörs av avrinning från tidigare regn som magasinerats tillfälligt i avrinningsområdet plus den fördröjda grundvattenavrinningen från det aktuella regnet. För beräkning av basflödet i Sala har valts den exponentiella recessionsmodellen.

$Q_t = Q_0 k^t$

Q_t = basflödet vid tiden t

Q_0 = basflöde vid tiden $t=0$

k = exponentiell recessionskonstant

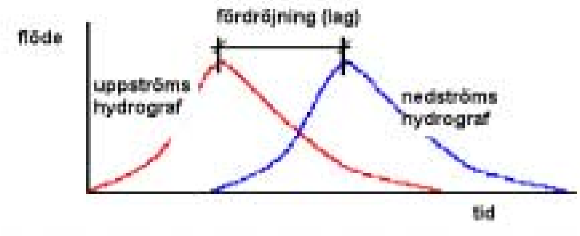


Figur 5.3 ***Principskiss över förhållandet mellan ytavrinning och basflöde.***

Initiellt basflöde, recessionskonstant och ett gränsvärdesflöde anges. Gränsvärdesflödet definierar punkten på hydrografen där basflödet ersätter ytavrinningen som källan till avrinning från avrinningsområdet.

5.4 Modellering av utjämning i vattendrag

Eftersom tillgången på data för vattendragen i Sala är begränsad har den enklaste av modellerna för utjämningsberäkning, ”Lag”modellen, valts. Inflödeshydrografen fördröjs med en angiven tid (lag) utan att någon dämpning av flödet sker. Utflödeshydrografen har alltså samma utseende som inflödeshydrografen men med en förskjutning i tiden.



Figur 5.4 ***Fördröjning enligt "Lag"modellen***

5.5 Modellering av reservoarer

Magasinering i reservoarer beskrivs i HEC-HMS genom kontinuitetsekvationen:

$$\frac{I_t + I_{t+1}}{2} - \frac{O_t + O_{t+1}}{2} = \frac{S_{t+1} - S_t}{\Delta t}$$

I_t=inflöde vid tiden t

I_{t+1}=inflöde vid tiden t+1

O_t=utflöde vid tiden t

O_{t+1}=utflöde vid tiden t+1

S_{t+1}=Magasinering vid tiden t+1

S_t= magasinering vid tiden t

Δt=tidsintervall mellan t och t+1

Förhållandet mellan nivå, magasinering och utflöde anges. Detta innebär en förenkling eftersom de större reservoarerna i Sala regleras med luckor och utflödet därmed inte enbart är beroende av nivån i reservoarerna.

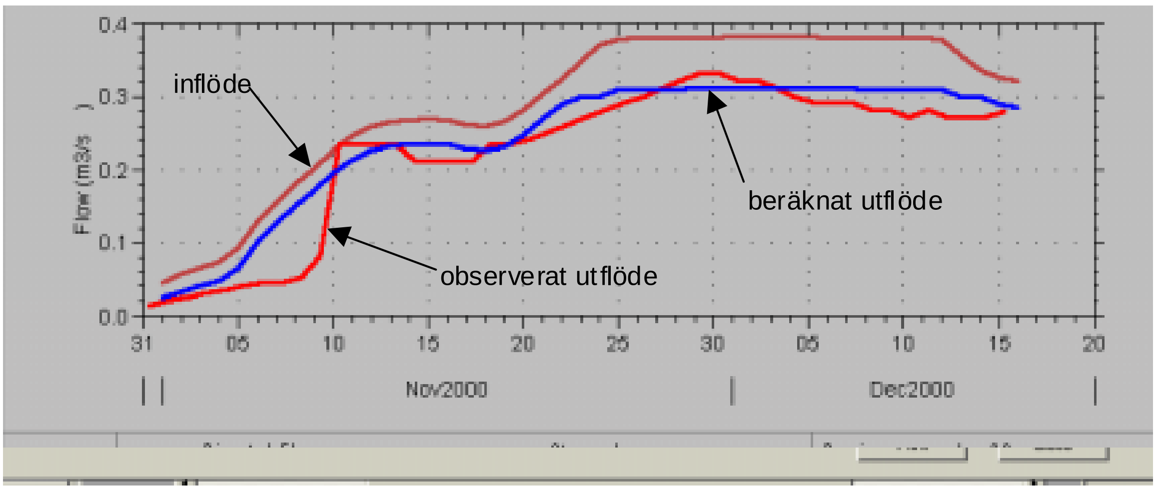
5.6 Kalibrering av modellen

I HEC-HMS kan en automatisk kalibrering av modellparametrarna utföras genom optimeringsberäkningar. Eftersom det i Sala inte existerar några kontinuerliga flödesdata över en längre period har inte det automatiska optimeringsalternativet använts. Istället har kalibreringen gjort manuellt genom grafisk jämförelse av beräknade flöden och observerade flöden.

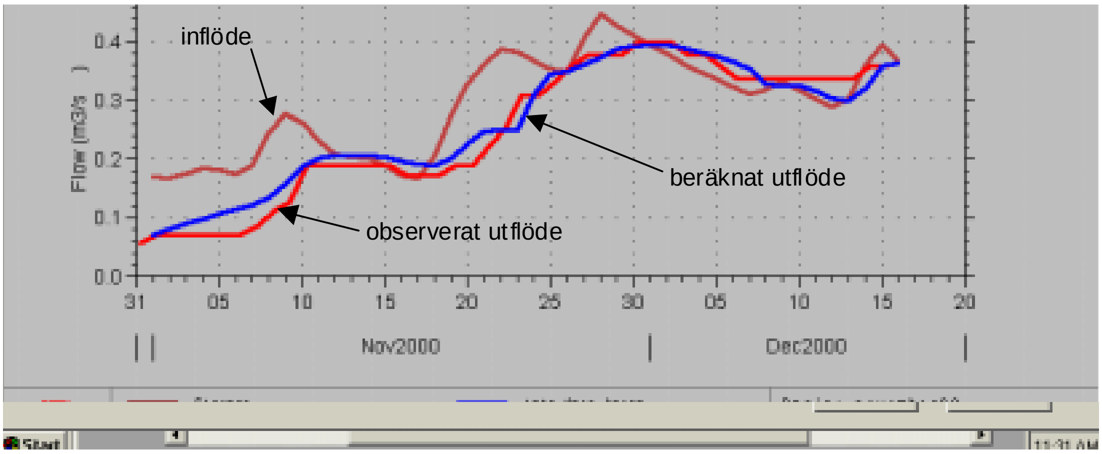
Modellen har kalibrerats för en regnstorm under perioden 1 november - 15 december 2000. Återkomsttiden för november flödet 2000 har uppskattats av SMHI till 25 år. Valet av denna period för kalibrering baseras på att det är det högsta flöde där flödesmätningar utförts i Sala och tillgången på uppmätta flöden är god. Dessutom var perioden snöfri så någon hänsyn behövde inte tas till snö.

Novemberflödet 2000 kan ses som en övre gräns för vad vattensystemet klarar av att hantera på ett säkert sätt med befintliga förhållanden.

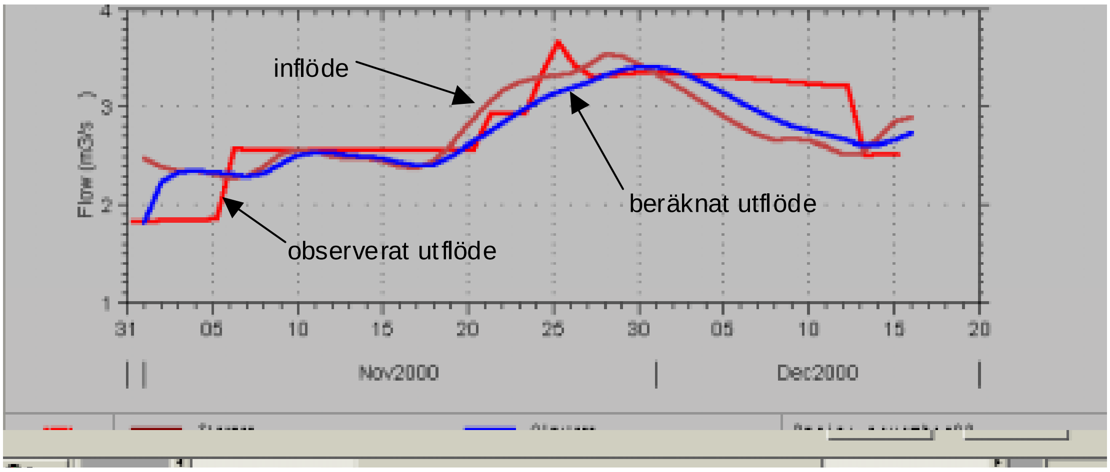
I diagrammen visar röd kurva observerat utflöde och blå kurva visar beräknat utflöde.



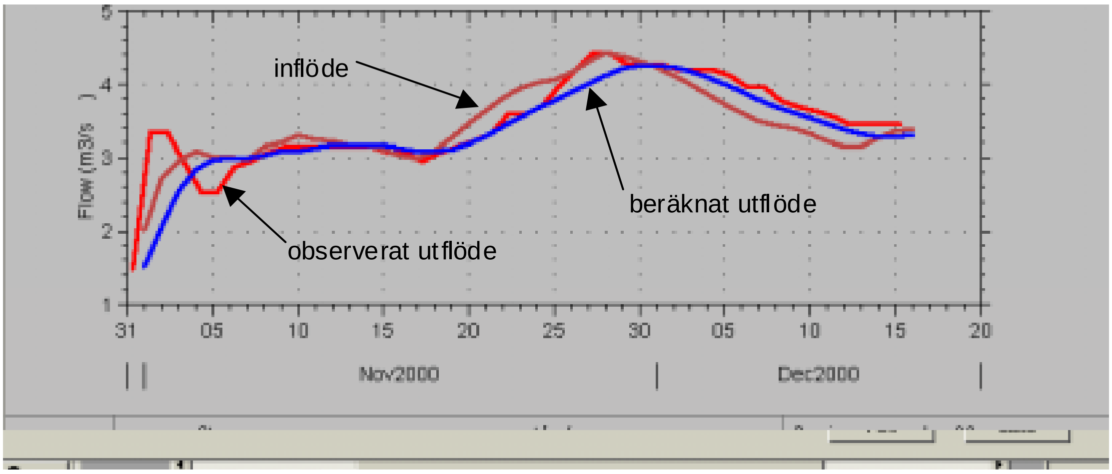
Figur 5.5 ***Kalibrering vid Storljusen november 2000***



Figur 5.6 ***Kalibrering vid Harsjöarna november 2000***



Figur 5.7 ***Kalibrering vid Olov Jons damm november 2000***

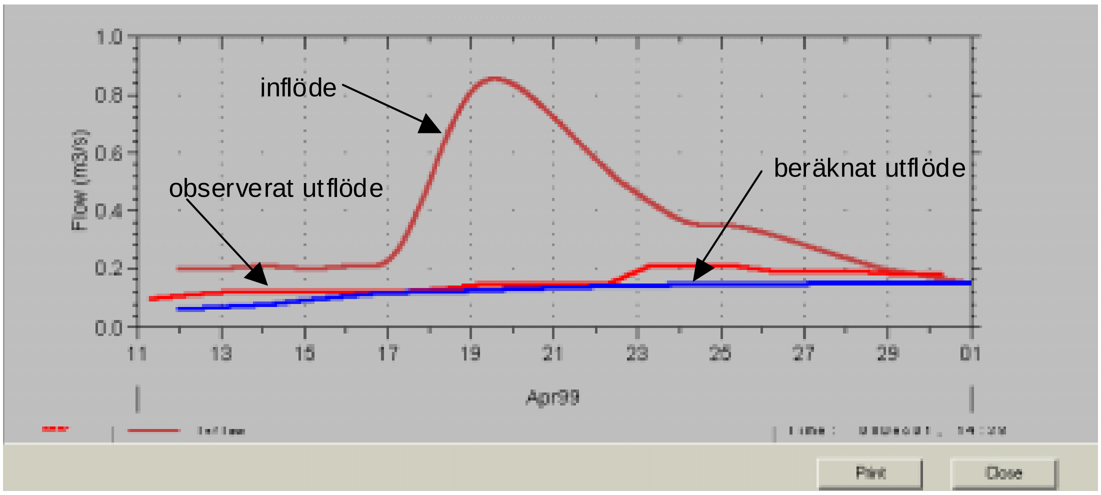


Figur 5.8 ***Kalibrering vid Långforsen november 2000***

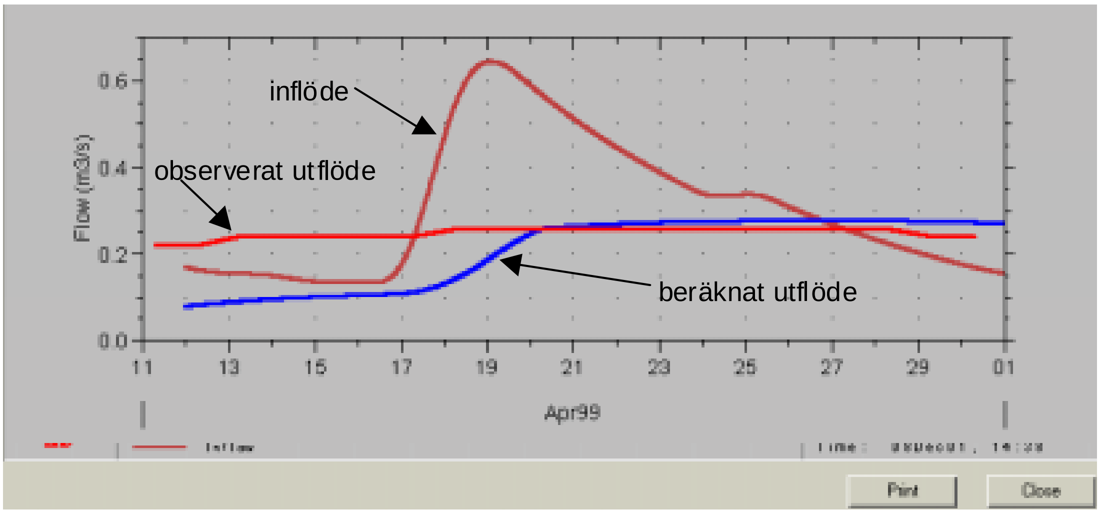
5.7 Validering av modellen

Beräknat flöde kan stämma väl överens med observerat efter en kalibrering trots ”fel” parametervärden. För att kontrollera att modellantagandena är rimliga görs därför en validering av modellen där beräknade flöden jämförs med observerade för en annan period än den som använts för kalibrering.

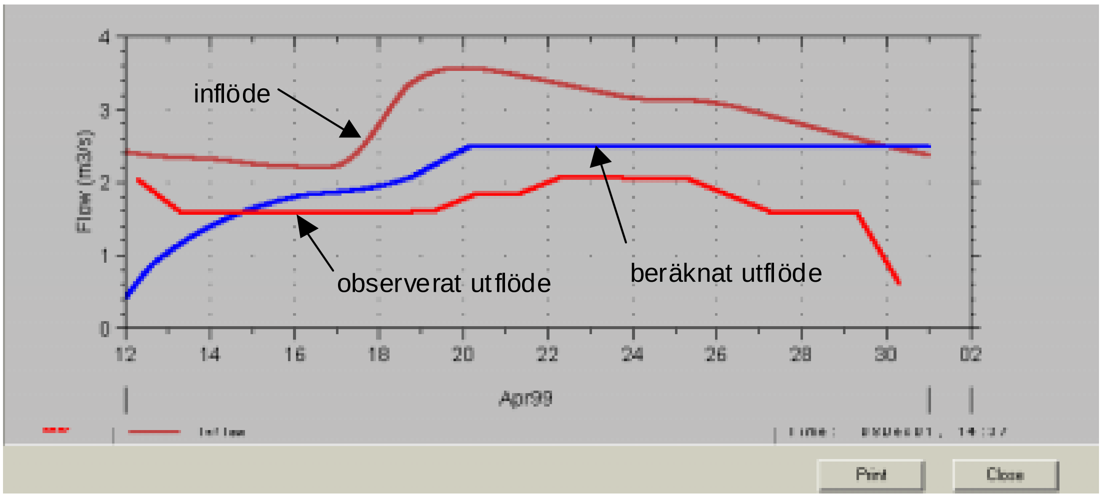
Validering av modellen för Sala har gjorts för en regnstorm under perioden 12 april - 30 april 1999. Valideringen har använts för att bekräfta rimligheten i den framkalibrerade modellen. På grund av skillnader mellan förhållanden under april och november kan inte full överensstämmelse förväntas.



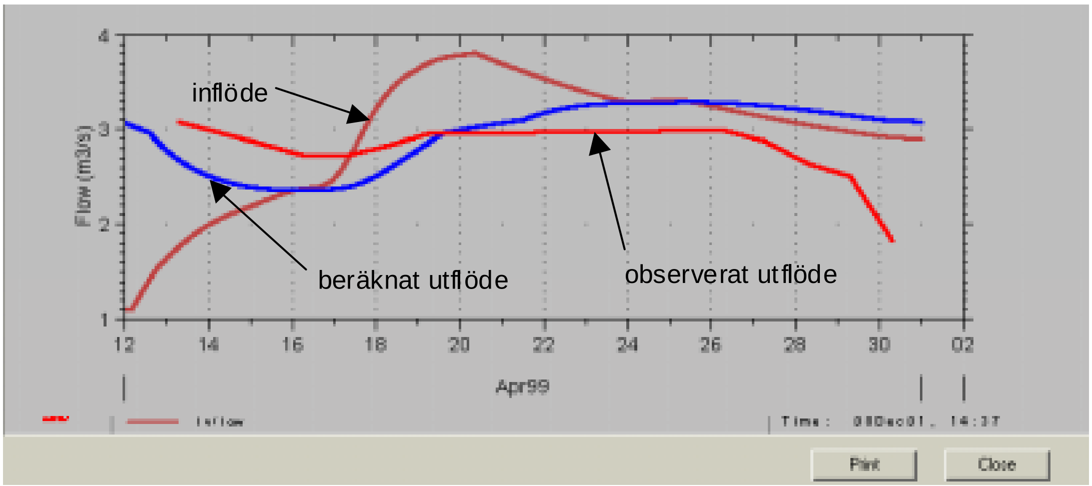
Figur 5.9 ***Validering vid Storljusen april 1999***



Figur 5.10 ***Validering vid Harsjöarna april 1999***



Figur 5.11 ***Validering vid Olov Jons damm april 1999***



Figur 5.12 ***Validering vid Långforsen april 1999***

6 BESKRIVNING AV AVRINNINGSOMRÅDET I SALA

6.1 Beskrivning av avrinningsområdet

Avrinningsområdet till Långforsen är 84 km^2 och har i modellen delats in i 16 delavrinningsområden. Avrinningsområdet består av 68 % skog, 12 % myrmark, 9 % sjöar och vattendrag, 5 % bebyggd mark och 6 % odlad mark (Chenvey 2000).

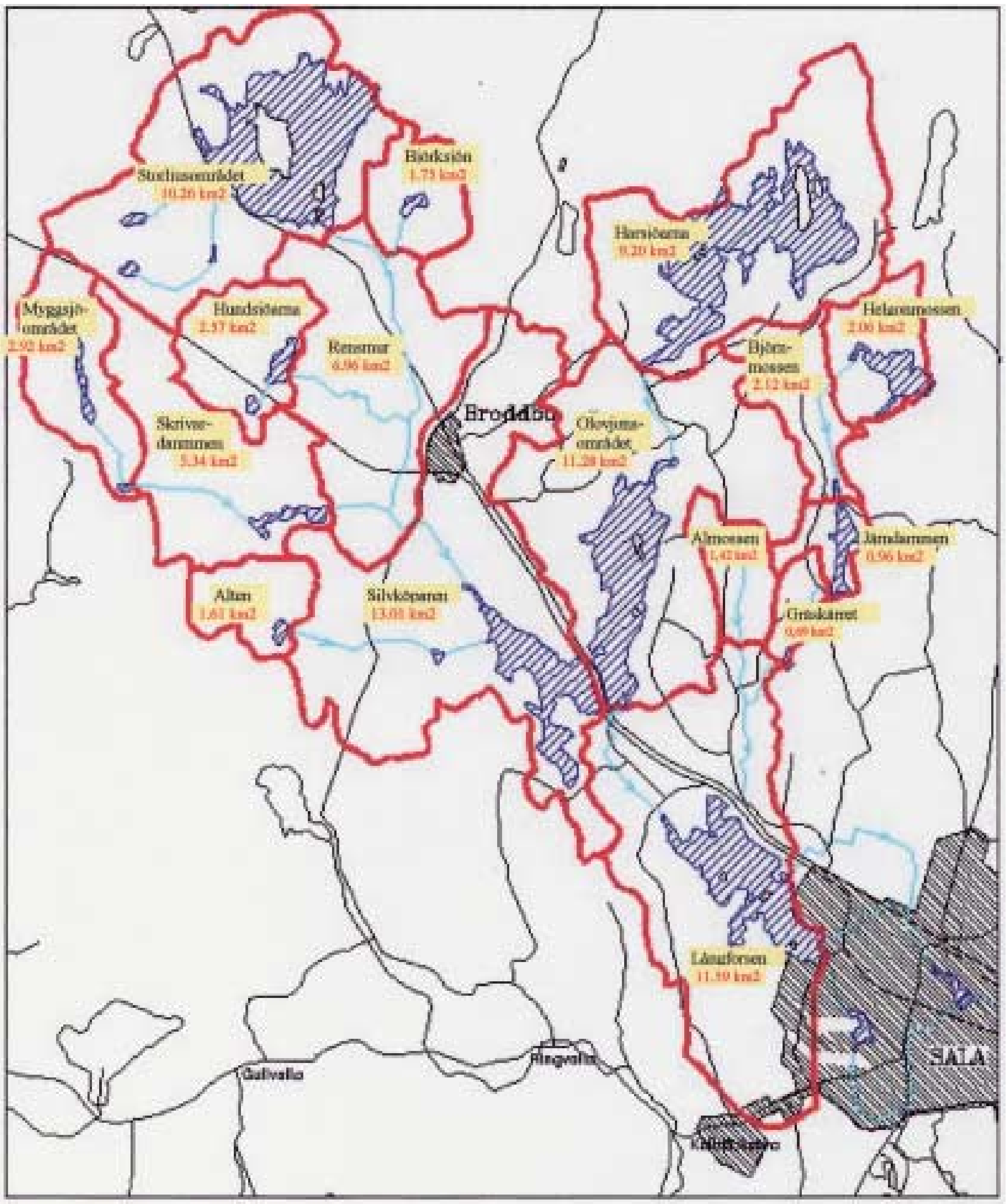
Sala ligger i gränszonen mellan Bergslagen och Mälardalen och avrinningsområdet ligger i olika klimatzoner. Mellan de nordvästra delarna av området och området kring Sala centrum kan det ofta skilja några grader i temperatur med de kallaste temperaturerna i de nordvästra delarna av avrinningsområdet.

Reglering

Enligt Sala kommun kan en reglering under en högflödessituation se ut enligt tabell 6.1. Vid simulering av dimensionerande klass I flöde har två olika principer använts. Dels har modellen körts med tappning enligt tabell 6.1 under antagande att dammarna är tillräckligt höga för att undvika överströmning. Dels har modellen körts med tillräcklig tappning ur sjöarna för att undvika överströmning av befintliga dammkrön. För 5-, 10-, 30- och 100-års regn har modellen endast körts med reglering enligt tabellen.

Läckage

Läckage genom dammvallarna vid Storljusen, Olov Jons damm och Långforsen uppskattas vara relativt omfattande – i storleksordningen några tiotal liter per sekund. Detta har tagits hänsyn till i modellen.



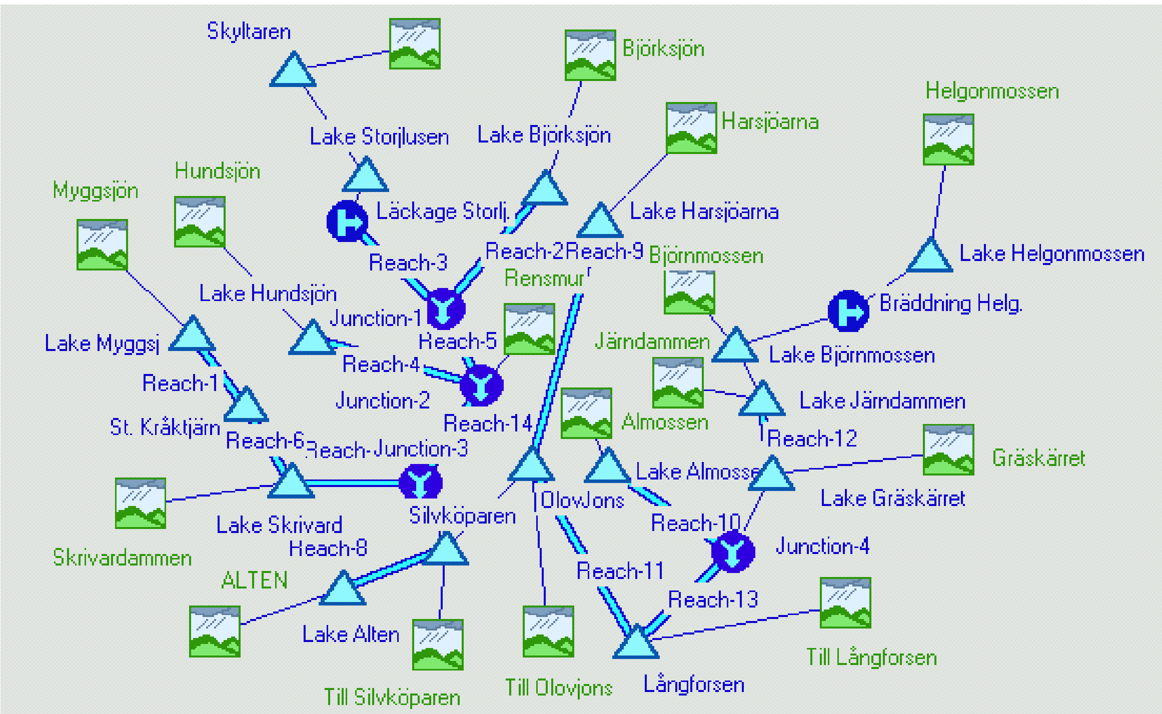
Figur 6.1 ***Delavrinningsområdena i Sala***

Tabell 6.1 ***Uppskattad trolig reglering under en högflödessituation***

SJÖ	INITIELL VATTENNIVÅ (m.ö.h.)	TAPPNING
Långforsen	+65.21	upp till +65.31: 0.5m³/s +65.31: 3.0m³/s +65.36: 4.0m³/s +65.41: 4.5m³/s +65.60: 5.5m³/s +65.80: 6.5m³/s
Olov Jons damm	+71.85	upp till +71.90: 0.3m³/s +71.90: 2.0m³/s +71.95: 2.5m³/s +72.00: 3.0m³/s +72.10: 4.4m³/s +72.50: 4.7m³/s
Storljusen	+91.60	upp till +91.65: 0.03m³/s +91.65: 0.05m³/s +91.70: 0.2m³/s +92.00: 0.3m³/s
Harsjöarna	+80.98	upp till +81.08: 0.01m³/s +81.08: 0.2m³/s +81.13: 0.3m³/s +81.18: 0.4m³/s

6.2 Befintliga förhållanden

Modellen över området är i princip uppbyggd av tre komponenter – delavrinningsområden, reservoarer samt förbindelser mellan de olika reservoarerna.



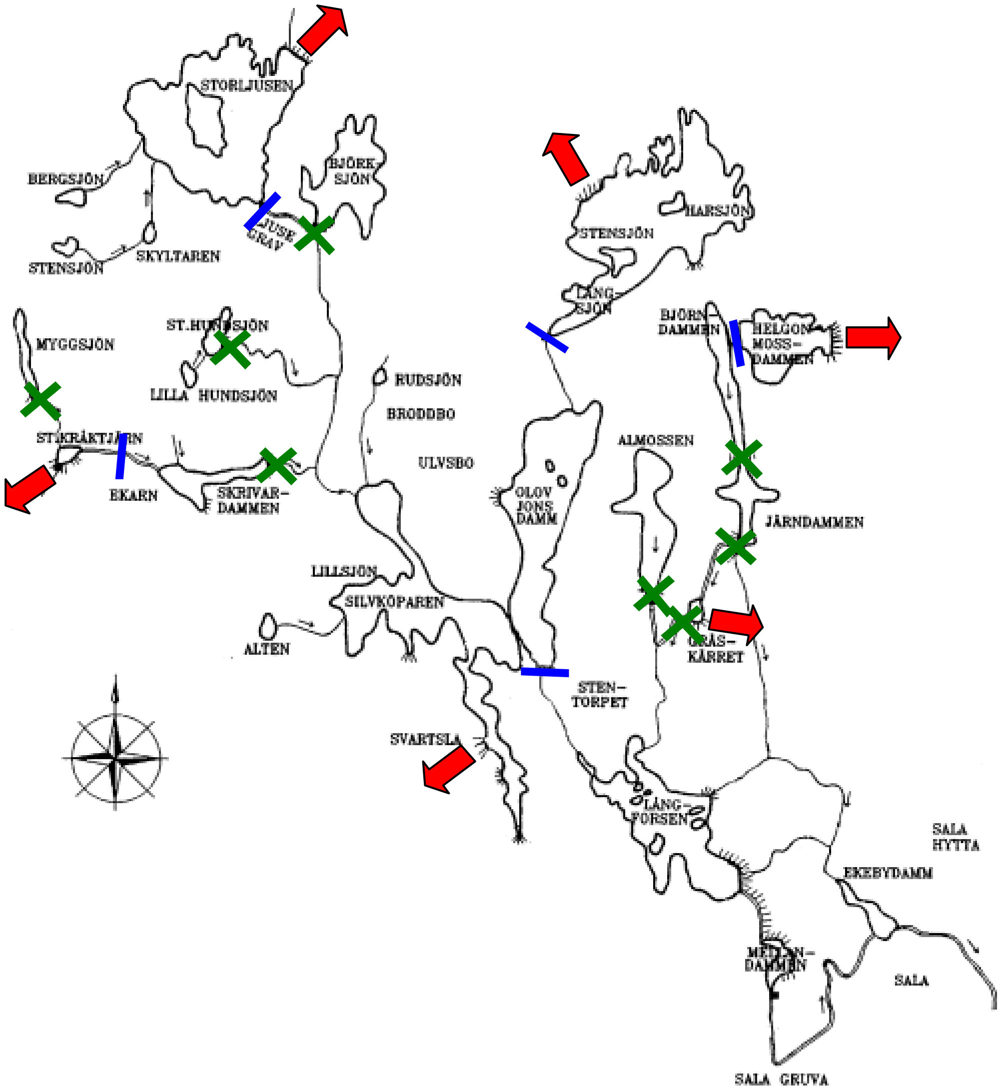
Figur 6.2 ***Avrinningsområdet med befintliga förhållanden beskrivet i HEC-HMS***

6.3 Efter införande av flödesdämpande åtgärder

Sala kommun har föreslagit vissa åtgärder för att höja dammsäkerheten i området. Åtgärderna innefattar höjning av dammkrön, strypning av flöden samt avledning av flöden vid vissa tidigare utrivna fördämningar. De planerade åtgärderna redovisas i figur 6.3. Bräddningen simuleras genom att i modellen införa komponenter där en definierad del av flödet avleds från systemet.

Tabell 6.2 ***Planerad höjning av dammkrön***

RESERVOAR	BEFINTLIG GENOMSNITTLIG NIVÅ DAMMRÖN (m.ö.h.)	PLANERAD GENOMSNITTLIG NIVÅ DAMMKRÖN (m.ö.h.)	PLANERAD GENOMSNITTLIG HÖJNING AV DAMMKRÖN (m)
Långforsen	+65.80	+65.95	0.15
Silvköparen	+72.30	+72.60	0.30
Olov Jons	+72.60	+72.60	-
Almossen	+78.70	+78.90	0.20
Gräskärret	+78.60	+78.60	-
Järndammen	+80.10	+80.20	0.10
Björnmossen	+82.00	+82.00	-
Helgonmossen	+83.10	+83.40	0.30
Harsjöarna	+81.50	+81.75	0.25
Skrivardammen	+87.50	+87.60	0.10
St Kråktjärn	+97.80	+97.80	-
Myggsjön	+102.85	+102.95	0.10
St Hundsjön	+107.10	+107.20	0.10
Björksjön	+96.30	+96.60	0.30
Storljusen	+92.10	+92.30	0.20

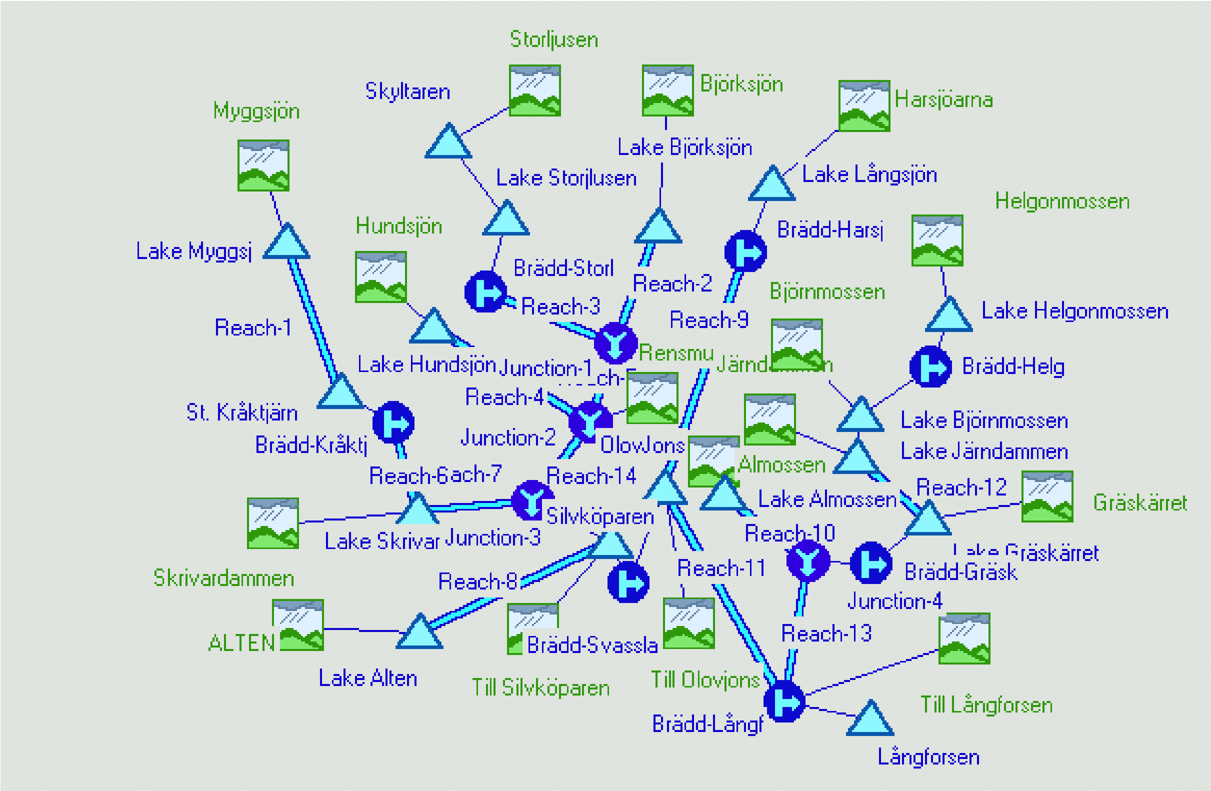


Bräddning (Vattnet leds bort från systemet till mindre översvämningskänsliga delar.)

Strypning (Avbördningen stryps till ca 0.1 m^3/s för att minska belastningen på dammarna nedströms.)

Optimal magasinering (Avbördningen anpassas för att minska belastningen på dammarna nedströms så mycket som möjligt.)

Figur 6.3 ***Föreslagna åtgärder för flödesdämpning i systemet***



Figur 6.4 ***Avrinningsområdet efter införande av flödesdämpande åtgärder beskrivet i HEC-HMS***

7 Resultat

Resultaten från modellkörningarna med befintliga förhållanden är redovisade i tabellform i bilaga 1a, medan resultaten efter införande av flödesdämpande åtgärder är redovisade i bilaga 1b.

7.1 Flödessituationen i området

En körning av modellen med ett 30-års regn resulterar i överströmning av Silvköparen och Harsjöarna. Om tappningen optimeras vilket i praktiken betyder att varaktighet och frekvens hos regnet är känt i förväg, är det möjligt att hantera ett 30-års regn utan överströmning av dammkrön.

Ett 100-års regn resulterar i överströmning av Silvköparen och Harsjöarna medan vattenståndet i Långforsen precis når dammkrön.

Ett dimensionerande klass I flöde resulterar i överdämning av både Storljusen, Harsjöarna, Silvköparen, Olov Jons och Långforsen. I Olov Jons damm når vattennivån ca 0.6 m över dammkrön medan vattennivån i Långforsen når ca 1.4 m över dammkrön.

Huvuddelen av inflödet till Långforsen produceras i de västra delarna av avrinningsområdet medan vattnet som kommer från Storljusen, Harsjöarna och Helgonmossen inte har någon betydande inverkan på det dimensionerande klass I flödet.

Enligt Sala kommun transporteras ungefär 24 miljoner m^3 vatten ut från systemet under ett normalår. Under 2000 när höga flöden inträffade både i juli och november var motsvarande siffra 38 miljoner m^3. För att undvika överströmning av dammkrön under ett dimensionerande klass I flöde måste nästan lika mycket vatten transporteras ut ur systemet under en månad som under hela år 2000.

7.2 Känslighetsanalys av resultaten

För att få en uppfattning om betydelsen av de olika antaganden som gjorts vid modelleringen har modellen även körts med vissa modifieringar av antagandena.

7.2.2 Dimensionerande regn

Beroende på om Lognormal fördelning eller Gumbel fördelning använts vid frekvensanalys av regnet skiljer det 3 cm i resulterande maximal vattennivå i Långforsen vid 100-års regn och 1 cm vid 30-års regn.

7.2.3 Sammanslagning av Silvköparen och Olov Jons damm

Silvköparen och Olov Jons damm förbinds via en vägtrumma. På grund av begränsad kapacitet i trumman kan vattenytan vid höga flöden vara högre i Silvköparen än i Olov Jons damm. Det är dock osäkert exakt hur stort flödet mellan Silvköparen och Olov Jons damm är. För att få en uppfattning om hur flödesbilden skulle förändras om Silvköparen och Olov Jons slogs samman till ett magasin kördes modellen även med förutsättningen att Silvköparen och Olov Jons är ett sammanhängande magasin. Resultaten är redovisade i bilaga 1a och 1b.

7.3 Jämförelse med resultat enligt SMHIs studie

Resulterande vattennivå i Långforsen den 31 augusti 1987 med dimensionerande klass I-flöde och tappning enligt tabell 6.1 är +67.20. Motsvarande värde i SMHI studien är +66.75. Dessa värden kan inte jämföras rakt av eftersom tappningsstrategierna som användes i SMHI studien skiljer sig från tappningstrategierna enligt tabell 6.1.

7.4 Inverkan av vågor

I angivna högsta vattenstånd ingår inte våguppspolning och snedställning av vattenytan. I SMHI studien från 1994 har vågornas inverkan beräknats med resultat enligt tabell 7.1.

Tabell 7.1 ***Våguppspolning och snedställning av vattenytan (Olofsson et al. 1994)***

RESERVOAR	UPPSPOLNING VID OORDNAD STENFYLLNING	UPPSPOLNING VID ORDNAD STENFYLLNING	VATTENYTANS SNEDSTÄLLNING
Storljusen	0.94 m	1.13 m	0.07 m
Harsjöarna	0.82 m	0.98 m	0.05 m
Olov Jons damm	0.83 m	1.0 m	0 .09 m
Långforsen	0.79 m	0.94 m	0.08 m

8 OSÄKERHETER OCH BEGRÄNSNINGAR I MODELLEN

Modellen begränsas av den knappa tillgången på flödesdata för kalibrering och validering. Kontinuerliga flödesdata över en längre period existerar inte utan mätningar har i princip endast utförts vid de tillfällen man gjort regleringsändringar. Detta betyder att en del flödestoppar kan ha missats.

Nederbördsmängderna kan variera lokalt och det kan finnas skillnader mellan nederbörden i aktuellt område och vid SMHIs mätstation som ligger ca 3 km utanför Sala. Dock är de lokala skillnaderna troligtvis inte så stora under hösten eftersom de konvektiva regnen uppträder främst under sommaren.

Avrinningsområdet i Sala består till stor del av myrmark. Då de hydrologiska egenskaperna hos myrmarker är dåligt kända och det dessutom är okänt vilken typ av myrmark det är i Sala, har parametrar som infiltration och magasineringsförmåga endast kunnat uppskattas mycket grovt.

Eftersom den hydrologiska modellen endast kalibrerats för november 2000, bör den endast användas för simulering av höststormar. Några tillförlitliga värden fås inte om modellen används för simulering av flöden under vinter, vår och sommar. Återkomsttiden för det flöde som använts vid kalibreringen är i storleksordningen 25 år. Vid användning av modellen för att utreda dammsäkerheten är det istället aktuellt att simulera ett flöde med en återkomsttid som troligtvis överskrider 10000 år. Hur pass väl anpassad den framkalibrerade modellen är för simulering av ett så extremt flöde är därmed osäkert.

Möjliga felkällor vid bestämning av regnen med olika återkomsttid utgör också en osäkerhet.

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Bilaga 1a

Tabell 1. 5-års regn - Tappning enligt Sala kommuns regleringsstrategier

Resultat från modellkörning med 5-års regn. Period: 1 augusti 1987 till 31 augusti 1987. Tappning antas ske enligt Sala kommuns regleringsstrategier och dammkrön antas tillräckligt höga för att undvika översvämning. 5-års regn bestämt med Log Normal fördelning. Dimensionerande regn startar 1/8 1987.

Reservoar	**Bef.höjd vallkrön** (m.ö.h.)	**Bef. normal-vattenstånd** (m.ö.h.)	**Max vattenstånd** (m.ö.h.)	**Max inflöde** (m3/s)	**Max utflöde genom utskov** (m3/s)	**Datum för max vatten-stånd**	**Datum för max inflöde**	**Totalt utflöde genom utskov** (1000 m3)
Storljusen	92.10	91.60	91.86	1.7	0.3	18/8	10/8	618
Björksjön	96.30	94.75	95.27	0.5	0.2		10/8	357
Hundsjön	107.10	106.70	106.82	1.2	0.8		10/8	550
Myggsjön	102.85	101.85	102.20	1.1	1.1		10/8	717
St Kråktjärn	97.80	96.55	96.82	1.1	1.1		10/8	717
Skrivardammen	87.50	86.14	86.59	2.8	2.3		10/8	1580
Alten			78.78	0.7	0.4		10/8	521
Harsjöarna	81.50	80.98	81.44	1.0	0.4	29/8	11/8	763
Helgonmossdammen	83.10	82.95	83.18	0.5	0.1		10/8	138
Bräddn. Helgonmossd.					0.4			523
Björndammen	82.00	79.72	79.72	0.4	0.4		10/8	316
Järndammen	80.10	79.72	79.80	0.5	0.3		1/8	411
Almossen	78.70	76.60	76.75	0.4	0.3		10/8	541
Gräskärret	78.60	78.10	78.61	0.5	0.6		13/8	889
Silvköparen	72.30	71.85	72.33	8.5	2.8	14/8	10/8	6067
Olov Jons damm	72.60	71.85	72.07	4.3	4.0	14/8	12/8	8068
Långforsen	65.80	65.21	65.54	5.8	5.2	18/8	13/8	10675

Om Silvköparen och Olov Jons ses som ett sammanhängande magasin:

Silvköparen + Olov Jons	72.60	71.85	72.29	10.0	4.5	13/8	11/8	7598
Långforsen	65.80	65.21	65.63	6.6	5.5	18/8	12/8	10254

Tabell 2. 10-årsregn - Tappning enligt Sala kommuns regleringsstrategier

Resultat från modellkörning med 10-års regn. Period: 1 augusti 1987 till 31 augusti 1987. Tappning antas ske enligt Sala kommuns regleringsstrategier och dammkrön antas tillräckligt höga för att undvika överströmning. 10 års regn bestämt med Log Normal fördelning. Dimensionerande regn startar1/8 1987.

Reservoar	**Bef.höjd vallkrön** (m.ö.h.)	**Bef. normal-vattenstånd** (m.ö.h.)	**Max vattenstånd** (m.ö.h.)	**Max inflöde** (m3/s)	**Max utflöde genom utskov** (m3/s)	**Datum för max vatten-stånd**	**Datum för max inflöde**	**Totalt utflöde genom utskov** (1000 m3)
Storljusen	92.10	91.60	91.91	1.9	0.3	18/8	10/8	623
Björksjön	96.30	94.75	95.32	0.5	0.3		10/8	384
Hundsjön	107.10	106.70	106.85	1.4	0.9		10/8	591
Myggsjön	102.85	101.85	102.25	1.3	1.3		10/8	761
St Kråktjärn	97.80	96.55	96.85	1.3	1.3		10/8	762
Skrivardammen	87.50	86.14	86.66	3.3	2.8		10/8	1709
Alten			78.98	0.8	0.5		10/8	544
Harsjöarna	81.50	80.98	81.51	1.2	0.4	30/8	11/8	768
Helgonmossdammen	83.10	82.95	83.21	0.5	0.1		10/8	143
Bräddn. Helgonmossd.					0.4			611
Björndammen	82.00	79.72	79.72	0.5	0.4		10/8	347
Järndammen	80.10	79.72	79.85	0.5	0.4		1/8	454
Almossen	78.70	76.60	76.76	0.4	0.3		10/8	600
Gräskärret	78.60	78.10	78.61	0.6	0.7		13/8	975
Silvköparen	72.30	71.85	72.55	10.3	3.0	14/8	10/8	6448
Olov Jons damm	72.60	71.85	72.10	4.6	4.4	14/8	11/8	8572
Långforsen	65.80	65.21	65.63	6.5	5.5	18/8	13/8	11391

Om Silvköparen och Olov Jons ses som ett sammanhängande magasin:

Silvköparen + Olov Jons	72.60	71.85	72.41	12.0	4.6	14/8	10/8	8269
Långforsen	65.80	65.21	65.74	7.1	5.7	20/8	11/8	11158

Tabell 3. 30-årsregn - Tappning enligt Sala kommuns regleringsstrategier

Resultat från modellkörning med 30-års regn. Period: 1 augusti 1987 till 31 augusti 1987. Tappning antas ske enligt Sala kommuns regleringsstrategier och dammkrön antas tillräckligt höga för att undvika överströmning. 30 års regn bestämt med Log Normal fördelning. Dimensionerande regn startar1/8 1987.

Reservoar	**Bef.höjd vallkrön** (m.ö.h.)	**Bef. normal-vattenstånd** (m.ö.h.)	**Max vattenstånd** (m.ö.h.)	**Max inflöde** (m3/s)	**Max utflöde genom utskov** (m3/s)	**Datum för max vatten-stånd**	**Datum för max inflöde**	**Totalt utflöde genom utskov** (1000 m3)
Storljusen	92.10	91.60	91.98	2.4	0.3	19/8	10/8	640
Björksjön	96.30	94.75	95.43	0.6	0.3		10/8	427
Hundsjön	107.10	106.70	106.90	1.6	1.1		10/8	657
Myggsjön	102.85	101.85	102.30	1.6	1.6		10/8	832
St Kråktjärn	97.80	96.55	96.90	1.6	1.5		10/8	832
Skrivardammen	87.50	86.14	86.74	4.0	3.4		10/8	1909
Alten			79.14	1.0	0.8		10/8	575
Harsjöarna	81.50	80.98	81.64	1.5	0.4	31/8	11/8	779
Helgonmossdammen	83.10	82.95	83.24	0.6	0.1		10/8	151
Bräddn. Helgonmossd.					0.5			741
Björndammen	82.00	79.72	79.72	0.6	0.4		10/8	398
Järndammen	80.10	79.72	79.94	0.6	0.4		11/8	525
Almossen	78.70	76.60	76.79	0.5	0.4		10/8	690
Gräskärret	78.60	78.10	78.61	0.8	0.8		13/8	1112
Silvköparen	72.30	71.85	72.86	12.9	3.1	14/8	10/8	6987
Olov Jons damm	72.60	71.85	72.19	5.3	4.4	16/8	11/8	9324
Långforsen	65.80	65.21	65.76	7.4	5.9	19/8	12/8	12306

Om Silvköparen och Olov Jons ses som ett sammanhängande magasin:

Silvköparen + Olov Jons	72.60	71.85	72.60	14.9	4.7	14/8	10/8	9255
Långforsen	65.80	65.21	65.79	7.7	6.4	18/8	11/8	12261

Tabell 4. 100-årsregn - Tappning enligt Sala kommuns regleringsstrategier

Resultat från modellkörning med 100-års regn. Period: 1 augusti 1987 till 31 augusti 1987. Tappning antas ske enligt Sala kommuns regleringsstrategier och dammkrön antas tillräckligt höga för att undvika överströmning. 100 års regn bestämt med Log Normal fördelning. Dimensionerande regn startar 1/8 1987.

Reservoar	**Bef.höjd vallkrön** (m.ö.h.)	**Bef. normal-vattenstånd** (m.ö.h.)	**Max vattenstånd** (m.ö.h.)	**Max inflöde** (m3/s)	**Max utflöde genom utskov** (m3/s)	**Datum för max vatten-stånd**	**Datum för max inflöde**	**Totalt utflöde genom utskov** (1000 m3)
Storljusen	92.10	91.60	92.05	3.6	0.3	20/8	10/8	643
Björksjön	96.30	94.75	95.55	0.7	0.4		10/8	465
Hundsjön	107.10	106.70	106.95	2.0	1.4		10/8	714
Myggsjön	102.85	101.85	102.37	1.9	1.9		10/8	897
St Kråktjärn	97.80	96.55	96.96	1.8	1.8		10/8	897
Skrivardammen	87.50	86.14	86.83	4.7	4.1		10/8	2091
Alten			79.30	1.2	1.1		10/8	609
Harsjöarna	81.50	80.98	81.78	1.8	0.4	31/8	11/8	784
Helgonmossdammen	83.10	82.95	83.28	0.7	0.1		10/8	160
Bräddn. Helgonmossd.					0.6			880
Björndammen	82.00	79.72	79.76	0.7	0.6		10/8	453
Järndammen	80.10	79.72	80.04	0.7	0.6		11/8	601
Almossen	78.70	76.60	76.82	0.5	0.4		10/8	775
Gräskärret	78.60	78.10	78.62	0.9	1.0		13/8	1252
Silvköparen	72.30	71.85	73.18	15.5	3.1	15/8	10/8	7257
Olov Jons damm	72.60	71.85	72.27	5.7	4.5	16/8	11/8	9773
Långforsen	65.80	65.21	65.79	8.0	6.4	17/8	11/8	12861

Om Silvköparen och Olov Jons ses som ett sammanhängande magasin:

Silvköparen + Olov Jons	72.60	71.85	72.84	17.9	4.7	15/8	10/8	9857
Långforsen	65.80	65.21	65.84	8.4	6.5	18/8	11/8	12892

Tabell 5. Klass-I flöde - Tappning enligt Sala kommuns regleringsstrategier

Resultat från modellkörning med dimensionerande regnsekvens enligt Flödeskommitténs riktlinjer. Tappning antas ske enligt Sala kommuns regleringsstrategier och dammkrön antas tillräckligt höga för att undvika överströmning. För totalt utflöde avser första värdet perioden 1 augusti till 31 augusti 1987 medan värdet inom parentes avser perioden 1 augusti till 30 november 1987. Dimensionerande regn startar 7/8 1987.

Reservoar	**Bef.höjd vallkrön** (m.ö.h.)	**Bef. normal-vattenstånd** (m.ö.h.)	**Max vattenstånd** (m.ö.h.)	**Max inflöde** (m3/s)	**Max utflöde genom utskov** (m3/s)	**Datum för max vatten-stånd**	**Datum för max inflöde**	**Totalt utflöde genom utskov** (1000 m3)
Storljusen	92.1	91.60	92.89	7.3	0.3	2/9	16/8	695 (3054)
Björksjön	96.30	94.75	96.28	1.7	0.8		16/8	900 (1619)
Hundsjön	107.10	106.70	107.78	4.6	5.9		16/8	1430 (2289)
Myggsjön	102.85	101.85	102.90	4.4	4.2		16/8	1736 (3727)
St Kråktjärn	97.80	96.55	97.34	4.2	4.2		16/8	1734 (3726)
Skrivardammen	87.50	86.14	87.45	11.1	10.4		16/8	4321 (8483)
Alten			80.20	2.9	2.7		16/8	1141 (2075)
Harsjöarna	81.50	80.98	83.55	4.6	0.4	24/9	17/8	817 (3962)
Helgonmossdammen	83.10	82.95	83.60	1.7	0.1		16/8	183 (576)
Bräddn. Helgonmossd.					1.5			1227 (2735)
Björndammen	82.00	79.72	80.15	1.8	1.2		16/8	1002 (1550)
Järndammen	80.10	79.72	80.22	1.8	2.0		17/8	1368 (2030)
Almossen	78.70	76.60	76.97	1.2	0.7		16/8	1123 (2803)
Gräskärret	78.60	78.10	78.65	2.6	2.5		17/8	2502 (4520)
Silvköparen	72.30	71.85	76.71	39.4	3.1	30/8	16/8	7367 (30369)
Olov Jons damm	72.60	71.85	73.23	9.0	4.7	30/8	17/8	10193 (42227)
Långforsen	65.80	65.21	67.23	14.2	6.5	4/9	17/8	13456 (58288)

Om Silvköparen och Olov Jons ses som ett sammanhängande magasin:

Silvköparen + Olov Jons	72.60	71.85	75.61	44.3	4.7	30/8	16/8	10176 (41852)
Långforsen	65.80	65.21	67.27	14.4	6.5	4/9	17/8	13332 (57927)

Tabell 6. Klass-I flöde - Erforderlig tappning för att undvika överströmning

Resultat från modellkörning med dimensionerande regnsekvens enligt Flödeskommitténs riktlinjer. Erforderlig tappning för att undvika överströmning av dammkrön antas. För totalt utflöde avser första värdet perioden 1 augusti till 31 augusti 1987 medan värdet inom parentes avser perioden 1 augusti till 30 november 1987. Dimensionerande regn startar 7/8 1987.

Reservoar	**Bef.höjd vallkrön** (m.ö.h.)	**Bef. normal-vattenstånd** (m.ö.h.)	**Max vattenstånd** (m.ö.h.)	**Max inflöde** (m3/s)	**Max utflöde genom utskov** (m3/s)	**Datum för max vatten-stånd**	**Datum för max inflöde**	**Totalt utflöde genom utskov** (1000 m3)
Storljusen	92.10	91.60	92.09	7.3	3.9	19/8	16/8	3805 (5652)
Björksjön	96.30	94.75	96.28	1.7	0.8		16/8	900 (1619)
Hundsjön	107.10	106.70	107.09	4.6	4.3		16/8	1430 (2289)
Myggsjön	102.85	101.85	102.81	4.4	4.3		16/8	1736 (3727)
St Kråktjärn	97.80	96.55	97.35	4.3	4.3		16/8	1734 (3726)
Skrivardammen	87.50	86.14	87.45	11.3	10.5		16/8	4321 (8483)
Alten			80.20	2.9	2.7		16/8	1141 (2075)
Harsjöarna	81.50	80.98	81.50	4.6	4.5	17/8	17/8	3034 (6286)
Helgonmossdammen	83.10	82.95	83.09	1.7	0.1		18/8	184 (576)
Bräddn. Helgonmossd.					1.6			1240 (2410)
Björndammen	82.00	79.72	80.15	1.8	1.2		16/8	1004 (1550)
Järndammen	80.10	79.72	80.09	1.8	1.8		17/8	1357 (2023)
Almossen	78.70	76.60	76.97	1.2	0.7		16/8	1123 (2803)
Gräskärret	78.60	78.10	78.60	2.5	2.6		17/8	2498 (4518)
Silvköparen	72.30	71.85	72.30	40.7	40.7	16/8	16/8	19608 (33210)
Olov Jons damm	72.60	71.85	72.60	46.6	53.6	17/8	16/8	25946 (47461)
Långforsen	65.80	65.21	65.80	58.2	57.0	17/8	16/8	33173 (63544)

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Tabell 7. 30-års regn

Resultat från modellkörning med 30 års regn efter införande av dammsäkerhetshöjande åtgärder. Period: 1 augusti till 31 augusti 1987. 30 års regn bestämt med LogNormal fördelning. Dimensionerande regn startar1/8 1987.

Reservoar	**Bef. normal vatten-stånd** (m.ö.h.)	**Föreslagen höjd vallkrön** (m.ö.h.)	**Föreslagen högsta högvatten-yta** (m.ö.h.)	**Max inflöde** (m3/s)	**Max utflöde genom utskov** (m3/s)	**Max utflöde genom bräddning** (m3/s)	**Max vattenstånd** (m.ö.h.)	**Datum för max vatten-stånd**	**Datum för max inflöde**	**Totalt utflöde genom utskov** (1000 m3)	**Totalt utflöde genom bräddning** (1000 m3)
Storljusen	91.60	92.30	91.90	2.4	0.1	0.4	91.90	18/8	10/8	237	733
Björksjön	94.75	96.60	96.40	0.6	0.2		95.68		10/8	408	
Hundsjön	106.70	107.20	106.90	1.6	1.1		106.90		10/8	657	
Myggsjön	101.85	102.95	102.60	1.6	1.6		102.30		10/8	832	
St Kråktjärn	96.55	97.30	97.20	1.6	0.1	1.4	96.90		10/8	268	564
Skrivardammen	86.14	87.60	87.50	2.6	1.0		86.99		10/8	1336	
Alten				1.0	0.8		79.14		10/8	575	
Harsjöarna	80.98	81.75	81.40	1.5	0.1	0.6	81.40	18/8	11/8	210	961
Helgonmossdammen	82.95	83.40	83.10	0.6	0.1	0.5	83.10		10/8	217	682
Björndammen	79.72	82.00	81.60	0.6	0.2		80.07		10/8	378	
Järndammen	79.72	80.20	79.90	0.4	0.3		79.87		10/8	475	
Almossen	76.60	78.90	78.70	0.5	0.2		77.31		10/8	398	
Gräskärret	78.10	78.60	78.50	0.6	0.1	0.5	78.47		12/8	268	800
Silvköparen	71.85	72.60	72.50	10.3	4.8		72.50	12/8	10/8	6523	
Olov Jons damm	71.85	72.60	72.50	6.6	4.6		72.39	16/8	12/8	8494	
Långforsen	65.21	65.95	65.80	6.6	5.6		65.62	18/8	12/8	10843	

Om Silvköparen och Olov Jons ses som ett sammanhängande magasin:

Silvköparen + Olov Jon	72.60	71.85	72.50	12.2	4.6		72.42	14/8	37902	7999	
Långforsen	65.80	65.21	65.80	6.9	5.7		65.64	16/8	37933	10430	

Tabell 8. 100-års regn

Resultat från modellkörning med 100 års regn efter införande av dammsäkerhetshöjande åtgärder. Period: 1 augusti till 31 augusti 1987. 100 års regn bestämt med LogNormal fördelning. Dimensionerande regn startar1/8 1987.

Reservoar	**Bef. normal vatten-stånd** (m.ö.h.)	**Föreslagen höjd vallkrön** (m.ö.h.)	**Föreslagen högsta högvatten-yta** (m.ö.h.)	**Max inflöde** (m3/s)	**Max utflöde genom utskov** (m3/s)	**Max utflöde genom bräddning** (m3/s)	**Max vattenstånd** (m.ö.h.)	**Datum för max vatten-stånd**	**Datum för max inflöde**	**Totalt utflöde genom utskov** (1000 m3)	**Totalt utflöde genom bräddning** (1000 m3)
Storljusen	91.60	92.30	91.90	3.6	0.1	0.8	91.90	15/8	10/8	237	1184
Björksjön	94.75	96.60	96.40	0.7	0.3		95.82		10/8	444	
Hundsjön	106.70	107.20	106.90	2.0	1.3		106.90		10/8	714	
Myggsjön	101.85	102.95	102.60	1.9	1.9		102.37		10/8	897	
St Kråktjärn	96.55	97.30	97.20	1.9	0.1	1.7	96.96		10/8	268	629
Skrivardammen	86.14	87.60	87.50	3.1	1		87.25		10/8	1453	
Alten				1.2	1.1		79.30		10/8	609	
Harsjöarna	80.98	81.75	81.40	1.8	0.1	0.9	81.40	15/8	11/8	211	1218
Helgonmossdammen	82.95	83.40	83.10	0.7	0.1	0.6	83.10		10/8	219	829
Björndammen	79.72	82.00	81.60	0.7	0.2		80.21		10/8	411	
Järndammen	79.72	80.20	79.90	0.5	0.4		79.90		10/8	521	
Almossen	76.60	78.90	78.70	0.5	0.2		77.52		10/8	403	
Gräskärret	78.10	78.60	78.50	0.7	0.1		78.49		12/8	268	910
Silvköparen	71.85	72.60	72.50	12.1	2.5	5.0	72.50	12/8	10/8	5617	1588
Olov Jons damm	71.85	72.60	72.50	4.8	4.4		72.10	13/8	11/8	7806	
Långforsen	65.21	65.95	65.80	6.7	5.6		65.62	16/8	12/8	10376	

Om Silvköparen och Olov Jons ses som ett sammanhängande magasin:

Silvköparen + Olov Jon	72.60	71.85	72.50	14.28	4	2	72.5	13/8	1078	7404	1487
Långforsen	65.80	65.21	65.80	6.8	5.5		65.6	15/8	37933	10051	

Tabell 9. Klass-I flöde

Resultat från modellkörning med dimensionerande regnsekvens enligt Flödeskommitténs riktlinjer efter införande av dammsäkerhetshöjande åtgärder. För totalt utflöde avser första värdet perioden 1 augusti till 31 augusti 1987 medan värdet inom parentes avser perioden 1 augusti till 30 november 1987. Dimensionerande regn startar7/8 1987.

Reservoar	**Bef. normal vatten-stånd** (m.ö.h.)	**Föreslagen höjd vallkrön** (m.ö.h.)	**Föreslagen högsta högvatten-yta** (m.ö.h.)	**Max inflöde** (m3/s)	**Max utflöde genom utskov** (m3/s)	**Max utflöde genom bräddning** (m3/s)	**Max vattenstånd**	**Datum för max vatten-stånd**	**Datum för max inflöde**	**Totalt utflöde genom utskov** (1000 m3)	**Totalt utflöde genom bräddning** (1000 m3)
Storljusen	91.60	92.30	91.90	7.3	0.1	5.3	91.90	17/8	16/8	248 (958)	3931 (5166)
Björksjön	94.75	96.60	96.40	1.7	0.8		96.29		16/8	886 (1619)	
Hundsjön	106.70	107.20	106.90	4.6	3.7		106.89		16/8	1435 (2290)	
Myggsjön	101.85	102.95	102.60	4.4	4.4		102.59		16/8	1736 (3727)	
St Kråktjärn	96.55	97.30	97.20	4.4	0.1	4.2	97.19		16/8	268 (1054)	1467 (2671)
Skrivardammen	86.14	87.60	87.50	7.4	6.7		87.50		16/8	2847 (5808)	
Alten				2.9	2.7		80.20		16/8	1141 (2075)	
Harsjöarna	80.98	81.75	81.40	4.6	0.1	4.1	81.39	18/8	17/8	229 (1015)	3105 (5275)
Helgonmossdammen	82.95	83.40	83.10	1.7	0.1	1.6	83.10		16/8	240 (637)	1184 (2349)
Björndammen	79.72	82.00	81.60	1.8	0.2		81.37		16/8	421 (1605)	
Järndammen	79.72	80.20	79.90	1.2	0.9		79.88		16/8	821 (2095)	
Almossen	76.60	78.90	78.70	1.2	0.2		78.54		16/8	387 (2245)	
Gräskärret	78.10	78.60	78.50	1.6	0.1	1.6	78.49		16/8	268 (1046)	1701 (3552)
Silvköparen	71.85	72.60	72.50	34.7	2.5	33.1	72.49	16/8	16/8	5725 (16708)	9086 (9107)
Olov Jons damm	71.85	72.60	72.50	6.6	4.7		72.49	24/8	17/8	9777 (25746)	
Långforsen	65.21	65.95	65.80	11.3	6.5	4.3	65.80	26/8	18/8	12481 (36237)	1573 (1573)

Om Silvköparen och Olov Jons ses som ett sammanhängande magasin:

Silvköparen + Olov Jon	72.60	71.85	72.50	39.8	2.5	36.4	72.50	17/8	16/8	5313 (19967)	13744 (14409)
Långforsen	65.80	65.21	65.80	8.0	5.8		65.67	19/8	17/8	10411 (32032)	

CONFERENCE PROCEEDINGS

Dam Safety Evaluation in Sala, Sweden
Proceedings from Safety, Risk and Reliability – Trends in Engineering, Malta 2001

Design flood for dams
Proceedings from ICOLD European Symposium, Norway, 2001

Dam Safety Evaluation in Sala, Sweden

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Summary

In Sweden the Swedish guidelines for design flood determination is used when evaluating dam safety. In the city of Sala dam safety is not satisfying according to these guidelines. The dam safety in the area is evaluated using a risk approach and the suitability of the Swedish guidelines for design flood in this special case is analysed.

Keywords: dam safety, risk, Sala, design flood

1. Introduction

In the city of Sala, located in the central part of Sweden, 110 km west of Stockholm, silver mining was going on for many centuries. In order to secure the supply of waterpower needed for the mining, an extensive water system with dams, canals and regulations were built.

When the municipality of Sala took over the water system in the beginning of the 1990s, it turned out that the dam safety was not satisfying enough according to the new Swedish guidelines for design flood determination.

A problem is that the oldest dams were built already during the 16th century and they are classified as historical monuments.

In this paper a risk approach is used in order to evaluate the dam safety of the water system and to evaluate whether or not it is reasonable to use the design flood recommended by the Swedish guidelines for design flood determination in this special case.

In order to answer the above questions the following problems are analyzed:

- What are the consequences and probability of a dam failure in Sala?
- What is satisfying dam safety, i.e. what risk can be accepted and who is to decide about it?
- How is contradicting interests like the value of historical monuments to be valued in relation to the dam safety?

2. Spillway design flood determination

There are different principles connected with the determination of spillway design flood. The flood frequency methods are based on a statistical evaluation of historical flood observations. Distribution functions are fitted to observed extreme values and extrapolated to the desired return periods.

Another design principle is to maximise the flood generating factors like precipitation and snow melt and convert these factors to a flood by the use of a hydrological model.

A third principle is the use of risk analysis, where the consequences of a conceivable dam failure is estimated and the design flood is determined through an iterative process where costs and risks are evaluated.

A forth principle is to use empirical rules with an implicit level of safety. An empirical rule where the dams were designed for a flood equal to the highest recorded discharge with an addition of 10 to

20 % were used in Sweden before the new Swedish guidelines for flood determination came. The doubling of the largest peakflow recorded at the dam site is another of these empirical rules that has been used as design flood around the world.

Each of these design principles has its advantages and disadvantages. In Sweden the principle with maximisation of the flood generating factors is used.

3. Design flood for dams in Sweden

Until 1990 Sweden had no guidelines for determination of the design flood. However a practice developed where the dams were designed for a flood equal to the highest recorded discharge with an addition of 10 to 20 %. This often equals a flood with a return period of 100 years.

In 1990, the Committee for Design Flood Determination presented a report with guidelines for determination of design floods for dams in Sweden [1]. The design flood is based on a consequence classification of dams. This classification is based on the marginal damage that a conceivable dam break at a certain dam could cause.

The dams are divided in two consequence classes, I and II, where dams in class I constitutes the highest risk defined as a non-negligible risk to human life or other bodily injury or a clear risk of major economic damage. The design flood for dams in consequence class I shall be simulated by applying an accepted hydrological model using a combination of unfavourable meteorological and hydrological conditions.

4. Risk analysis in dam safety

The use of risk analysis when evaluating dam safety has until now only been used to a limited extent in Sweden. Internationally, mainly in Canada, the US, Australia and South Africa risk analysis is used more and more frequently in connection with dam safety and research in the field of finding practical solutions for the use of risk analysis in dam safety is in full progress.

The Swedish guidelines for design flood determination uses to some extent a risk approach when dividing dams into consequence classes. However the classification only considers the consequences and not the probability of a possible dam failure. The use of only two consequence classes means that the design flood for a dam where a dam failure constitutes a risk to one human life is the same as for a dam where a dam failure constitutes a risk to 10 000 human lives. One could argue that the classification of dams should reflect the reality as good as possible. The use of ten consequence classes probably gives a closer picture of reality than the use of two classes and a complete risk analysis for the individual dam in turn probably gives a closer picture of reality than the use of consequence classification with ten classes. The problem is that the closer to reality the dam safety guidelines come the more difficult and expensive they are to apply.

The use of risk analysis in dam safety has been criticised because factors that cannot be measured in economic terms like the loss of human lives and environmental values are involved. Another argument against the use of risk analysis is that it might be expensive to use due to the complexity of the method.

The fact that the economical resources of the power industry and other dam owners available for dam safety improvements are not unlimited speaks for the use of risk analysis. A risk approach is a way of securing that good priorities are done between different dams and different safety measures.

5. Case study: The water system of Sala

5.1 Description of the water system

The water system consists of five major lakes/reservoirs, namely Storljusen, Stensjön, Silvköparen/Olof Jons dam and Långforsen. Besides the water system contains some minor lakes. According to a summary of the reservoirs of the water system the total available storage volume is 16.4 million m^3 [2]. Since this data is almost 70 years old it should be taken only as an approximate value.

Two of the dams, Olov Jons and Långforsen are classified as class I dams. Olov Jons dam is a fill dam with a length of 700 m and a height varying between 0 and 5 m. The storage volume at full supply level is 4.34 million m^3. The dam is equipped with one spillway. Långforsen is a 300 m fill dam with a height varying between 0 and 4 m and a storage volume at full supply level of 1.85 million m^3. The dam is equipped with 2 spillways.

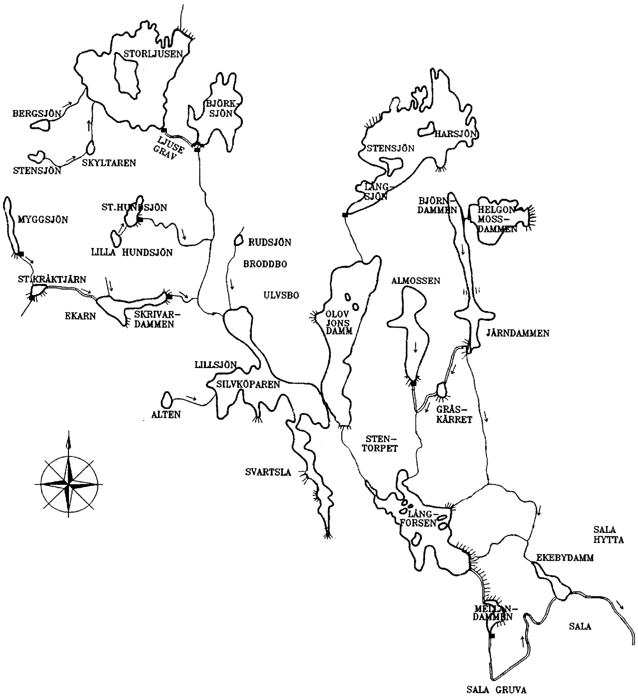

Fig. 1 The water system of Sala

5.2 Potential risk sources

Extreme floods are not the only risk posed to the dams in Sala. Below are listed the potential risk sources.

- Trees growing on the dam crest - Trees growing on the dam crest might fall down which might lead to extensive damage and leakage through the dam which in turn might result in dam failure.
- Leakage through the dams - Ongoing leakage through the dams might lead to undermining and dam failure.
- Extreme floods - An extreme flood might lead to overtopping of the dams and a resulting dam failure. Overtopping of the dams is highly probable to cause a dam failure.
- Lack of observation - Observations of water level in the reservoirs are done manually. During autumn and spring the dams are inspected on a daily basis, while in summer the dams are inspected once a month except during heavy precipitation when they are visited more often. Since there is no automatic measuring of water levels it is possible to miss some high floods. And even if the high floods are observed they may not be observed in time to open the discharge facilities, warn the rescue service and evacuate the public.
- Spillways blocked with debris - The spillways may be blocked by debris preventing full discharge.
- Gates getting stuck - The discharge facilities are regulated manually on a need basis. It is possible that the gates are left unregulated for long periods which might result in them getting stuck and being impossible to open when necessary.
- Untrafficable roads - High floods and the need for emergency actions often coincide with bad weather situations like strong wind, snow and high precipitation. A bad weather situation might make it impossible to reach the discharge facilities and dams.

- Lack of automatic alarm and warning system.
- Human factor - The observations of water level and the operation of the discharge facilities of the reservoirs are done manually which makes the dam safety of Sala highly dependent on the human factor.

5.3 Special features of the dams in Sala compared to hydropower dams

The features of the dams in Sala differ from those of Swedish hydropower dams. The main differences are:

- The dams in Sala are much older than the hydropower dams. Some of the dams were built already during the 16th century while the majority of the high hydropower dams in Sweden were constructed during the 1950s, -60s and -70s [3].
- The dams in Sala are classified as cultural historical monuments.
- The dams are small. The highest section of Olov Jons dam is 5 m and the highest section of Långforsen is 4 m.
- The reservoirs are relatively small. The total reservoir volume of Långforsen, Olov Jons and Silvköparen is approximately 8 million m^3. The largest Swedish reservoir, Suorva has a volume of 900 million m^3.
- The flows are small. The design flood in Sala according to the Swedish guidelines for flood determination is in the range of 10 to 20m^3/s [4] while the design flood for some class-I dams in the larger rivers in the north of Sweden can reach values exceeding 2500 m^3/s [5]. The marginal damage of a dam failure at Långforsen could however be considerably larger than the marginal damage of a dam failure in one of the larger Swedish rivers, since a flood with a magnitude exceeding 2500 m^3/s will probable cause large damages even without a dam failure. In Sala on the other hand the design flood is of such a modest magnitude that it will probably not cause any major damage if a dam failure does not occur.
- The reservoir regulation is not controlled by power production factors.
- The dams are not associated with any economic incomes in contrast to hydropower dams.

5.4 Consequences of dam failure

No dam break analysis has been done in order to analyse the consequences of a dam failure. However the Rescue service in Sala have done some rough estimations of the consequences of a conceivable dam failure at Olov Jons or Långforsen.

According to their estimation approximately 10 to 20 lives would be at risk if a dam failure occurs at Olof Jons dam. If a dam failure would occur at Långforsen approximately 10 lives would be at risk.

The Rescue service estimate that a dam failure at Långforsen would not pose a direct risk to human lives in the city of Sala. The economical damages however are estimated to hundreds of millions of Swedish crowns.

5.5 Probability of dam failure

Since the design flood according to the Swedish guidelines are determined by a deterministic method there is no return period connected with the value of the design flood. The return period or probability of occurrence of the design flood is necessary in order to be able to estimate the probability of dam failure caused by extreme floods. Consequently the probability of dam failure in Sala is impossible to estimate.

5.6 Contradicting interests

There is a contradicting interest between the preservation of the dams due to their historical value and the need for upgrading and repair in order to secure the dam safety. Permission from the county administrative board is necessary before any re-constructions are made.

The claim that any repairs and re-constructions should be done using old-fashioned methods and materials probably contradicts with claims of efficiency and good economy.

According to the county administrative board judgements are made from case to case and are based on discussion between the different interested parties.

5.7 Acceptable risk

According to the Swedish guidelines for flood determination any loss of life due to dam failure is unacceptable, that is a failure of Olov Jons dam or the dam of Långforsen is unacceptable. The risk acceptance criteria in Australia (ANCOLD), Canada (BC Hydro) and the Netherlands [6] for a dam with a potential loss of 10 lives gives that annual probabilities of dam failure exceeding 10^{-4} is unacceptable in all three countries.

The municipality of Sala has the opinion that a dam failure of either Olov Jons or Långforsen can not be allowed to happen.

5.8 Choice of design flood

For dams where a dam failure would result in loss of human lives the design flood used in most countries vary between the flood with a return period of 10 000 years and the PMF (Probable Maximum Flood). Since the Swedish guidelines use a deterministic method to determine the design flood there is no return period associated with it. However the return period of the design flood according to the Swedish guidelines has been appreciated on the average to exceed the 10 000 years flood.

The question is whether the special features of the dams in Sala compared to hydropower dams in Sweden make it unsuitable to use the design flood according to the Swedish guidelines.

6. Discussion and conclusions

As mentioned it is impossible to determine the probability of dam failure in Sala. However taking into account the age of the dams, the fact that maintenance was neglected for many years and that leakage through the dams occur, dam failure can not be dismissed as being highly improbable.

Approximately 10 to 20 lives would be at risk if a dam failure should occur at Olov Jons dam or Långforsen and the economical damages in the city of Sala are estimated to hundreds of millions of Swedish crowns. In order to analyze the consequences of a dam break in detail it is recommendable to perform a dam break analysis of the water system.

The consequences of a dam failure in Sala, the fact that the dams are over 400 years old and the comparison with acceptance criteria and design flood abroad together with the fact that the municipality of Sala considers a dam failure of Olov Jons or Långforsen as unacceptable brings on to the conclusion that the design flood according to the Swedish guidelines for flood determination is not a too strict demand in this special case. Experience shows that even highly improbable floods do actual occur from time to time. It is also important to point out that extreme floods are not the only risk posed to the dams in Sala. The different risk sources should be further analyzed and compared with each other in order to find the most efficient dam safety solution.

There is a contradicting interest between the dam safety requirements and the historical values of the dams and water system in Sala. Since a dam failure poses a risk to human lives safety must be prioritized. However great consideration should be taken to the historical values when choosing methods and materials for dam safety improvements.

There is no clear answer to the question What is satisfying dam safety? A comparison of acceptance criteria abroad shows that in practise a loss of 10 to 20 lives due to dam failure is unacceptable. The problem of limited economical resources however remains and priorities between different needs in a community are necessary. In the end the question of defining satisfying dam safety has to be a political decision.

Finally, since there can never be a total guarantee that a dam failure of Olov Jons dam or Långforsen will not occur, it is important to inform the inhabitants of the risk posed by the dams and put up an emergency action plan.

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Design flood for dams – analysis of the Swedish guidelines

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ABSTRACT: The Swedish guidelines for design flood determination from 1990 are analyzed and a comparison is made with design flood guidelines in other countries. Advantages and disadvantages with the present guidelines are discussed.

1 INTRODUCTION

According to international statistics overtopping is the cause of 1/3 of all dam failures (Graham 1995). And during the last 25 years dam failures due to overtopping caused approximately three deaths per year in the US. As a perspective approximately 5 000 pedestrians die in the US every year due to motor vehicle accidents (Graham 2000).

In 1990, the Committee for Design Flood Determination presented a report with guidelines for determination of design flood for Swedish dams (Flödeskommittén 1990). According to these guidelines the dams should be classified in three classes depending on the marginal consequences of a conceivable dam failure. Every dam where a dam failure would pose a risk to human lives belongs to the most severe class.

The question of the applicability of the guidelines for small dams, where only a few lives are at risk in case of a dam failure arose in connection with a dam safety evaluation of some minor dams in the city of Sala.

An analysis of the Swedish guidelines for design flood determination is done and a comparison is made with guidelines in other countries. The following questions are discussed: The use of deterministic versus probabilistic methods for design flood determination. Is the present consequence classification system satisfying? What impact will possible future changes like a climate change have on the applicability of the present guidelines? What could be the alternatives to the present guidelines?

2 SPILLWAY DESIGN FLOOD DETERMINATION

There are different principles connected with the determination of spillway design flood. One principle is the use of flood frequency methods, based on a statistical evaluation of historical flood observations. Distribution functions are fitted to observed extreme values and extrapolated to the desired return periods. The study of past or ancient flood events that occurred prior to direct measurement by modern hydrologic procedures may be used to supplement existing hydrologic data when performing a frequency analysis. Flood frequency analysis has the advantages that it is simple to apply and specifies the return period of the flood. The disadvantages are that runoff observations over long time periods are often missing, that the validity of frequency analysis is based on the presumption that conditions during the observations period do not change during the period to be predicted and that different distribution functions give different results.

Another design principle is to maximize the flood generating factors like precipitation and snow melt and convert these factors to a flood by the use of a hydrological model. The use of Probable Maximum Flood, PMF as design flood is an application of this principle. The PMF is defined as “the flood that may be expected from the most severe combination of critical meteorologic and hydrologic conditions that are reasonably possible in the drainage basin under study” (Graham 2000). Advantages with hydrological models compared to frequency analysis are that the models can be based on the actual properties of the watershed, that the models can be calibrated against available data and that they are easier to adjust to changes. Disadvantages are that unique parameter values are difficult to determine (different errors might compensate each other in the model), calibration for high observed floods may not be valid for extreme floods, properties of the watershed might differ from those during calibration of the model, calibration and validation of a hydrological model is dependent on statistical data, different models can give different results and finally there is no return period connected to the design flood.

A third principle for design flood determination is the use of risk assessment, where the probability and consequences of a conceivable dam failure is estimated and the design flood is determined through an iterative process where costs and risks are evaluated. The use of risk assessment has been criticized because factors that cannot be measured in economic terms are involved. And it relies on flood frequency analysis, since the probability of a certain flood has to be estimated. Another argument against the use of risk assessment is that it might be expensive to use due to the complexity of the method. The advantage with risk assessment is that it helps assuring that good priorities are made between different dam safety measures and that resources for dam safety improvements are used in an efficient way.

A forth principle not used so much today is to use empirical rules with an implicit level of safety. The doubling of the largest peak flow recorded at the dam site is an example of an empirical rule that has been used as design flood around the world.

3 DESIGN FLOOD FOR DAMS IN SWEDEN

Until 1990 Sweden had no guidelines for determination of design flood. However a practice developed where the dams were designed for a flood equal to the highest recorded discharge with an addition of 10 to 20 %. This often equals a flood with a return period of 100 years.

In 1990, the Committee for Design Flood Determination (Flödeskommittén 1990) presented a report with guidelines for design flood determination for dams in Sweden. The design flood is based on a consequence classification of the dams, based on the marginal damage that a conceivable dam break at a certain dam could cause.

The dams are divided in three consequence classes, I, II and III where dams in class I constitutes the highest risk defined as a non-negligible risk to human life or other bodily injury or a clear risk of major economic damage. The design flood for dams in consequence class I shall be simulated by applying an accepted hydrological model using a combination of unfavourable meteorological and hydrological conditions. For dams in consequence class II the design flood should be the flood with a return period of 100 years, determined by frequency analysis. Dams belonging to class III are not included in the guidelines.

The Swedish guidelines use a deterministic approach where a 14-day precipitation sequence based on the highest observed area precipitation is combined with snow melt and soil moisture conditions to produce the design flood. Regulation strategies and wind impact is also considered. The maximization of the flood generating factors are obtained mainly by a critical timing of the different flood generating factors and not so much by extrapolation of the single factors.

The judgement according to the Swedish guidelines is that the modelled design flood has a return period exceeding 10 000 years.

4 DESIGN FLOOD ABROAD

4.1 *Norway*

The Norwegian rules make a distinction between Dimensioning inflow and Probable maximum inflow (Flödeskommittén 1990). The dimensioning inflow is the flow the dam shall be able to handle under normal conditions, and it is assumed to have a return period of 1 000 years. This flood is determined with frequency analysis. The probable maximum inflow corresponds to PMF and is the flood the dam shall be able to handle without failure. The dams are classified in three classes according to consequences of failure. Dams in the low hazard class are only evaluated against the 1

000-year flood while dams in the high hazard class are always evaluated against Probable maximum inflow. The Norwegian guidelines for flood calculations are under revision (Pettersson 1998).

4.2 *Finland*
In Finland the dimensioning floods are determined with frequency analysis. The dams are classified in four different classes, P, N, O and T-dams. For dams in the highest class where dam failure poses an obvious danger to human lives, obvious sanitary danger or obvious considerable danger to environment or property, a dimensioning flood with a return period of 5 000 to 10 000 years should be used (Loukola et al. 1998).

4.3 *the US*
In the US the different dam owners use different guidelines for design flood determination. The US Bureau of Reclamation use risk assessment when determining the design flood. The consequences and probability of dam failure is considered and the design flood is determined by back-calculation. The present guidelines of the U.S. Army Corps of Engineers use different safety standards, depending on the consequences of a dam failure when determining the design flood. Dams placing human life at risk shall be able to safety pass the PMF. New probabilistic guidelines are currently under development.

4.4 *the UK*
In the UK dams are divided into four categories and the design flood depends on which category the dam belongs to. For dams in the highest category where a dam failure could endanger lives in a community, the PMF is used. While in most countries a dam failure is not accepted, the UK would accept a dam failure if a study shows that over all this would be more economic. If rare overtopping is tolerable a minimum standard for design flood can be used. If an economic study is warranted for dams belonging to the lowest categories a flood that minimizes spillway plus damage costs can be used. However this flood may not exceed the minimum standard flood (Minor 1998).

4.5 *France*
In France the Gradex, Gradient of Extreme Values, method is used where frequency analysis is applied to precipitation data instead of runoff data. For concrete dams with large risk the 5 000-year flood is used while for concrete dams with small risk the 1 000-year flood is used. For embankment dams the 10 000-year flood is used (Minor 1998).

4.6 *Canada*
In Canada the rules vary between the different provinces. In British Colombia and Ontario PMP-calculations and hydrological models are used while Hydro Quebec has developed their own method, based on dividing up and redistribution of existing measured precipitation series.

The Dam Safety Guidelines of the Canadian Dam Association stat that the IDF, Inflow Design Flood for high consequence dams should be between the 1 000-year flood and the PMF. High consequence dams are dams where some fatalities are expected. The sliding scale was probably intended to provide dam owners some flexibility to use judgement in the determination of IDF. There is however no legally defensible precedent for selecting anything other than the PMF for high consequence dams. The validity of applying PMF where it is not reasonable and practicable to upgrade a dam to the PMF is currently being questioned in Canada.

4.7 *Australia*
In 2000 the new Guidelines on Selection of an Acceptable Flood Capacity for Dams were published (ANCOLD 2000). In these new guidelines risk assessment is integrated in the determination of design flood.

The Acceptable Flood Capacity, AFC, for a specific dam is defined as “the overall flood capacity, including freeboard as relevant, which provides an appropriate level of safety against a flood initiated dam failure to protect the community and environment, to acceptable overall risk levels, within the total context of overall dam safety from all load cases”.

The risk procedure requires the owner, or other decision-maker, to take the responsibility to set the risk management criteria and then to make the decisions on the overall management, community and environment and political and legal issues, using the information provided by the risk study.

According to the AFC Guidelines the hydrologic safety should be assessed within the total load context, and not as a separate case, in order to achieve optimum safety and economy and not just concentrate on flood safety.

In cases where a detailed risk process is too costly and not practical the guidelines include a fallback alternative based on a hazard classification with five hazard categories based on the population at risk and the severity of damage and loss. For dams in the highest hazard categories the PMF should be used.

4.8 *Germany*

In Germany the flood with a return period of 1 000 years is used and a sufficient freeboard must be provided taking the PMF into account (Rettemeier 1998).

4.9 *Italy*

In Italy the flood with a return period of 1 000 years is used (Minor 1998).

4.10 *Spain*

In Spain the dams are classified according to size, potential hazard and type of dam. Two different floods are used, the design flood and the extreme flood or safety check flood. For dams in the highest hazard class the 1 000-year flood is used as design flood. The extreme flood for dams in the highest hazard class varies between the 5 000- and 10 000-year flood, where the higher value should be used for embankment dams. The operation during floods must not produce flows that create damages downstream that are higher than those which could be produced naturally without the existence of the reservoir (Minor 1998).

4.11 *Switzerland*

In Switzerland a design flood with a return period of 1 000 years is used. As a safety check the PMF is used, where the PMF is assumed to be 50 % higher than the design flood (Minor 1998).

4.12 *South Africa*

In South Africa envelope curves are used for the determination of design floods. Maximum flood peaks observed in a hydrologically homogenous region are plotted against catchment area and an envelope curve is drawn for the points. The curve is considered as the upper limit of expected flood peaks for the considered region. The corresponding flood peak is called Regional Maximum Flood, RMF, and is the flood used when evaluating the safety of a dam. The envelope curves are based on 519 maximum observed flood peaks in South Africa, Lesotho, Swaziland, Namibia, Botswana, Zimbabwe and Mozambique (ICOLD 1992). For spillway design the 1 in 200 year flood is used.

4.13 *Austria*

Due to the fact that practically all of the dams in Austria pose a risk of loss of human lives, the large dams have not been classified with regard to hazard. Large dams are dams higher than 15 m above foundation level or reservoirs with a capacity of more than 500 000 m^3. The spillways should be designed for a 5 000-year flood. Studies concerning PMF methods have been carried out, but the calculation of PMF seems extremely difficult for small catchments in mountainous regions (Melbinger 1998).

4.14 *the Netherlands*

In the Netherlands a water level that the dikes must be able to withstand is prescribed. The standard is expressed as the mean yearly exceedance frequency of the prescribed water level. It varies from 1/10 000 to 1/1 250 depending on the economic activities and size of population in the protected area.

A new safety approach based on the risk of flooding is under development. With this new approach the risk is expressed by multiplying the probability of flooding with its consequences, meaning that the safety can be increased not only by strengthening of the dikes or by lowering of the extreme water levels, but also by affecting the potential effects of flooding (Méndez 1998).

4.15 *the Czech Republic*

The dams in the Czech Republic are classified into three classes, A, B and C. For dams belonging to class A the lives of ten or more persons are endangered while for class B the lives of single persons are endangered. For dams in class C there is no probable loss of life. For class A dams the 10 000 year flood is used as design flood while for class B dams the 1 000-year flood is used. The flood with a return period of 100 years is used for dams belonging to class C (Macháček 1998).

4.16 *Comparison between the design flood in Sweden and abroad*

85 % of the dam spillways in the world have capacities that are based on the PMF or the 10 000-year flood (Fahlbusch 1999). Of the countries mentioned above Norway, the US, the UK and Canada use the PMF as dimensioning flood for the dams in the most serious risk class. The countries in Southern Africa use a design flood called the Regional Maximum Flood, RMF, based on over 500 observed maximum flood peaks.

Australia uses a risk-based approach where the overall dam safety is considered and not just the hydrologic load. In the US the Bureau of Reclamation already use risk assessment whereas the Army Corps of Engineers are currently developing probabilistic guidelines. In Canada and the Netherlands a risk-based approach is under development.

The other countries use a design flood based on frequency analysis with a return period varying between 1 000 years and 10 000 years. Some countries like Norway, Spain, Switzerland and South Africa makes a distinction between the spillway design flood and the flood used for dam safety evaluation.

The Swedish design flood for dams in consequence class I can be compared to the PMF. Though the factors used when calculating the Swedish design flood are put on a level that is touched upon once or a few times during the observation period. When calculating PMF on the other hand, the precipitation is usually increased to values exceeding the observed precipitation and the calculation is then modified by other factors.

The comparison of design flood between different countries is ambiguous. The hydrological load of the dam do not only depend on the inflow design flood but on the reservoir storage characteristics, the freeboard and spillway arrangements and the critical duration storm for routing the flood. Consequently it can be misleading to compare Inflow Design Flood, IDF, criteria. Australia uses the Dam Crest Flood, DCF instead of the IDF for comparison of safety. The DCF is defined as the flood event which, when routed through the reservoir, results in a still water level in the reservoir, excluding wave effects, which:

- For an embankment dam is the lowest point of the embankment crest;
- For a concrete dam is the uppermost level of the crest;
- For a concrete-faced rock fill dam is the lowest point of the crest.

5 FUTURE CHANGES THAT MIGHT AFFECT THE DESIGN FLOOD

5.1 *Climate change*

There is an ongoing discussion on a possible future climate change and the impacts such a climate change might have on the runoff pattern and specially on the magnitude and frequency of extreme floods.

Climate simulations by SWECLIM, Swedish Regional Climate Modelling Programme (SWECLIM 1998) gives a scenario of the climate in Sweden 100 years ahead, provided that no major reductions occur in the amount of discharge of greenhouse gases. The scenario is that around the year 2100 the temperature has risen about 5 ºC during winter and 2-3 ºC during summer. The precipitation scenario shows a rise in the northern part of Sweden of 20-30 % while the rise in southern Sweden is smaller. The rise in precipitation will to some extent probably be evened out by a higher evaporation.

According to SWECLIM (SWECLIM 1999) the probability of extreme floods will in general decrease, mostly because of a reduction in the spring flood. However the probability of large summer and autumn floods increases in the north. The report points out that the results are highly preliminary and should absolutely not be seen as forecasts.

According to a report on climate change impacts on runoff and hydropower in the Nordic countries the flood risk in large, continental catchments is expected to be reduced, while the flood risk in small catchments can increase (Saelthun et al. 1998). A warming of the climate could besides changes in precipitation and runoff possibly lead to stronger winds according to SWECLIM.

6 DISCUSSION

6.1 *Deterministic versus probabilistic methods for design flood determination*

Deterministic guidelines often use safety levels that are based on extreme events that are considered highly improbable but possible, like the PMF. This principle is used in Sweden when determining the design flood.

In Australia, Canada, the US and the Netherlands new probabilistic guidelines have recently been developed or are currently under development. And according to the Bureau of Reclamation in the US there has been an increasing trend in water resources analysis toward probabilistic design methods for evaluation of the effectiveness of different safety measures (US Bureau of Reclamation, 1997).

The design flood for class I dams in Sweden is often referred to as the 10 000 year flood. This is a serious misunderstanding. Since the guidelines are based on a deterministic method there is no return period connected with the design flood. In fact you can not determine if the design flood calculated is the 1 000-, 10 000-, or the 100 000 year flood.

In his article "Should dams be modified for the probable maximum flood?" Graham objects to the use of PMF for dam safety modifications due to the following causes: (1) larger spillway capacity may increase annual downstream flood losses, (2) benefit-cost ratios may be low, (3) construction accidents associated with dam modification may cause fatalities, and (4) the amount spent to save lives by making dams safer is often very high.

Probabilistic methods have the advantage over deterministic methods that they give an appraisal of the probability of dam failure. This is necessary if risk assessment is to be used. The problem is that the probabilities in question when dealing with extreme floods are so small and accordingly very difficult to estimate. In fact some argue that it is impossible to determine floods with as high return periods as 1 000 to 10 000 years.

About an existing dam that has been evaluated against the Swedish guidelines you can tell if it fulfils the requirements in the guidelines or not, but you can not say anything about how safe the dam is. Even when the most restrictive design criteria are applied the risk of dam failure, although very small can never be totally dismissed.

Deterministic methods on the other hand are not so dependent on statistical data and they are less sensitive to changes of the hydrological properties in a watershed. Considering a possible climate change might speak for the continued use of a deterministic approach.

6.2 *Classification of dams*

The Swedish guidelines only use three consequence classes. This results in major differences in the severity of consequences due to dam failure between different dams in the same class. The same design flood should be used for a dam where a dam failure would pose a threat to 1 human life as for a dam where a dam failure would lead to the loss of 10 000 human lives. And since the classification does not take the probability of failure into account the same design flood should be used no matter how high the probability of dam failure if lives are at risk. The terms used for describing the risks that a conceivable dam failure would pose are negligible-, non-negligible, considerable- and clear risk. How these terms are valued are open to subjectivity.

According to the guidelines it is not ethically defensible to let the safety level depend on an economical analysis when it comes to dams where the potential losses like the losses of human lives can not be evaluated in money. At the same time the guidelines state that the risk of dam failure shall be brought down to a level as low as possible with present knowledge, available technique and reasonable economical costs. In order to evaluate what is the level of reasonable economical costs, some sort of economical analysis has to be done taking both probability and consequences into account.

Since the economical resources of the power industry available for dam safety improvements are not unlimited, priorities need to be done between different dams. Is it then reasonable that the economical costs involved in fulfilling an acceptable safety level is the same for a dam where a dam failure leads to the loss of 1 life as the costs for a dam where a dam failure leads to the loss of 10 000 lives. And is it reasonable that the costs for dam safety modifications are independent of the probability of dam failure? The Swedish national road administration puts a value on human life in order to make priorities between different safety measures in the traffic. So why could it not be done when dealing with dam safety?

It is desirable that the classification of dams should reflect the reality as good as possible. The use of ten consequence classes probably gives a closer picture of reality that the use of two classes and a risk assessment taking both consequences and probability of a dam failure in concern for the individual dam in turn probably gives an even closer picture of reality. The problem is that the closer to reality the dam safety guidelines get the more difficult and expensive they most probably are to apply.

6.3 *Future changes affecting the hydrological load*

A future scenario with an increased frequency of extreme floods due to a global warming of the climate does not seem to be probable. Instead it seems like a warmer climate would even out the floods. However a change in the seasonal pattern of floods is likely to happen. The spring flood will be advanced in time and smaller while the floods during late summer and autumn probably will increase. Even during winter, high floods are possible in the future. High floods in autumn and winter can be troublesome since this is the time when the reservoirs are full. A normal high flood in connection with a full reservoir might pose just as high a risk as an extreme spring flood. Besides autumn floods are less predictable than the spring floods which might lead to an increased uncertainty in the flood estimates.

Another factor affecting the flood capacity of the dams is that a warmer climate might possibly lead to stronger winds.

6.4 *Alternatives for design flood determination in Sweden*

A possible consequence of this future scenario could be that the Swedish guidelines for design flood determination are modified so that more concern is put on the regulation strategy of the reservoirs.

The Swedish consequence classification system with three classes could be extended to more classes. As an example the Australian fallback alternative uses five hazard classes where a distinction is made between the number of lives at risk if a dam failure should occur. Namely; no life at risk, 1 to 10 lives at risk, 11 to 100 lives at risk, 101 to 1 000 lives at risk and finally more than 1 000 lives at risk.

There should exist an alternative for the dam owner to use risk assessment of the overall safety of the dam. And based on the results the dam owner should be able to choose another flood than the one prescribed in the Swedish guidelines for control of the dam safety. In this way greater consideration could be taken to the existence of warning systems and emergency plans. And more consideration could be taken to the special features of the single dam. In this respect more research in the field of assigning probabilities to extreme hydrologic events would be desirable.

The guidelines should be continually revised for instance every ten to fifteen years to take into account changes that occur.

7 CONCLUSIONS

Since the Swedish guidelines only use three consequence classes and concern is taken to the probability of dam failure there can be great differences in the present dam safety status between different class I dams which might lead to an inefficient use of resources for dam safety improvements.

The Swedish guidelines for design flood determination are based on the principle of using extreme floods that are highly improbable but possible. In other countries where like in Sweden deterministic methods are used there seems to be a switch over to probabilistic methods involving risk assessment. In Sweden there should exist an alternative for the dam owner to choose another design flood based on the results of a risk assessment of the safety of the dam.

A possible climate change with a change in the runoff pattern speaks for the continued use of a deterministic method like the present guidelines for design flood determination. However it is important that the guidelines are continually revised.

Finally attention should be paid on the fact that even if the most restrictive design criteria are applied to our dams, the risk of failure although very small can never be totally dismissed

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