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FLOOD HANDLING AND EMERGENCY ACTION PLANNING FOR DAMS

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SUMMARY

Even though dams are designed to bypass floods of significant magnitudes, floods less severe than the design flood may pose a threat to dams. Ongoing research into climate change also shows an increasing trend towards severe floods, that is an increased probability of floods exceeding the present design floods. Therefore, acquiring understanding of floods and risk reduction measures to mitigate any of their undesired effects is of great importance. Dam safety management in Norway has moved towards active use of risk analyses. At the same time, emergency planning and exercises are emphasized as necessary tools for handling abnormal situations such as severe floods. Few dam safety experts or dam owners have experienced large floods, which makes it difficult to assess the complexity of floods. Floods may also be difficult to assess fully by means of traditional risk analyses, as these normally focus on single dams. Floods have a certain geographical extent and must be expected to occur simultaneously in a system of dams and reservoirs.

This thesis hopes to extend knowledge of floods and dam safety. The main conclusion of a literature review of risk analysis and emergency planning is that human factor must be a focus. This is further supported by findings from the case studies of hazard floods. Emergency planning and exercises are believed to be of major importance to successful flood handling, but a survey of status for these issues in Norway shows that there is still work to be done. Many dam owners have not managed to start developing emergency action plans nor carry out emergency exercises. Not surprisingly, most of these are municipalities and private citizens, typical owners of smaller dams. Future revision of the emergency planning guidelines should take these findings into consideration. The authorities should bear in mind the need for alternative approaches to encourage these dam owners to develop emergency action plans. Possible problems related to development trends in our society also deserve attention, such as increased focus on cost-effective organizations at the expense of safety and the need for robust organizations and technical systems to handle future emergencies.

A study of selected flood events has been performed to provide a deeper insight into the complexity of floods. The selected cases represent both historical and recent floods, from regulated as well as unregulated rivers. It is believed that the cases presented here (supported by the referred material) can serve as a knowledge base for risk analyses and emergency planning. However, care must be taken when transferring experiences from floods and flood handling in time and space. Several of the cases demonstrate the vulnerability of spillway gates during floods. Eliminating spillway gates is seldom an option. Emphasis must

therefore be put on redundancies in technical systems and development of emergency procedures. Adequate resources, both with respect to personnel and material, are of vital importance to successful flood handling. Many of the cases revealed that local dam operators have a key role during floods because communication systems, access roads and power supplies tend to fail, especially during floods caused by heavy rain in combination with wind or lightning strike. Recent floods also demonstrate that pressure from media and other interested parties must be taken seriously. Many dam owners would probably benefit developing information plans.

A method, based on various data from previous floods, for the creation of reliable flood scenarios, to be used in either risk analyses or emergency exercises, is proposed. The method is tested on the Vinstra River Basin. The well-known "Storofsen " flood of 1789 has been simulated and used as a basic event. By using additional information from other relevant flood events, it has been possible to create a modern Storofsen-scenario. It is by nature difficult to test the credibility of a scenario, but attempts have been made to adapt the scenario for exercises and training purposes. The scenario has been applied in a river flood and accident simulator (RIFA).

PREFACE

This doctoral thesis provides a summary of literature reviews, field surveys, case studies and method development and was undertaken from 1998 to 2002 at the Department of Hydraulic and Environmental Engineering, NTNU. Financing of the study was provided mainly through the project "Safety of Structures in Rivers", which is part of the research program "Basic Energy Research" governed by the National Research Council of Norway (NFR). The Norwegian National Committee on Large Dams (NNCOLD), the Norwegian Water Resources and Energy Directorate (NVE), Glommen and Laagen Water Management Association (GLB), and the RIFA-project/EBL-Kompetanse have all contributed with partial financing, and thereby made it possible for me to complete this study. Cooperation with these organizations has made my work very interesting. I have gained valuable insights by being a member of the reference committee for new guidelines on risk analysis for dams issued in 2001, which among others things included a study visit to the US Bureau of Reclamation's Technical Service Center in Denver, Colorado in August 2000.

Many persons have contributed to this work, but unfortunately I am not able to thank them all. Prof. Dagfinn K. Lysne at the Department of Hydraulic and Environmental Engineering, NTNU, my supervisor who inspired me to start this study, sadly passed away in January 2000. His kind support and belief in my work has been very valuable. From March 2000, Prof. Haakon Støle was appointed as my new supervisor and has been a good mentor for the last part of my study.

I would also like to express sincere gratitude to Knut Alfredsen for all his help with the case study of Vinstra and for reading through parts of the manuscript for me. Cooperation with him and the others within the RIFA-project has been of great value for the outcome of this study, especially by allowing me to use the setup for the Vinstra River for testing of my Storofsen-scenario.

Valuable inputs in the form of data, discussions and prepared field trips in the Vinstra River Basin have been provided by GLB. Thanks go to Jens Kristian Tingvold who provided me with data from simulation of "Storofsen", Dan Lundquist and Gjermund Molle who have guided me on field trips and always been available for discussions, and the rest of the staff at GLB.

Thanks go to Nils Todal, Tormunn Skarstad, Knut Helge Kjærvik and others who have been helpful in my search for experiences and data on previous flood events. I would also like to thank all my former and new colleagues at NVE, and Morten Skoglund at SINTEF, who have provided me with data and been available for discussions.

I have really appreciated the good working environment and the practical assistance I have got from many of my colleagues at the Department of Hydraulic and Environmental Engineering, NTNU. Special thanks go to Hilde Marie Kjellesvig and the other doctoral students, Ragnhild Sundem, Brit Ulfsnes and Hilbjørg Sandvik. Thanks also to Leif Lia and Annette Semadeni-Davies for valuable comments to the thesis.

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1 INTRODUCTION

1.1 Background

Evidence of dam constructed more than 4500 years ago can be found in Egypt and the Middle East (Schnitter 1994). The first ancient dams were built mainly for flood control, soil conservation, irrigation and water supply; the dominant types were embankment and gravity dams. The dam with the longest operation time is probably Kofini Dam in Greece. Built around 1260 BC as an embankment dam between two walls of masonry, it is still fulfilling its purpose (river diversion). Some of the ancient dams failed and some were rebuilt, several times. In a number of cases dams were built with very solid cross-sections, possibly because their danger to downstream society was recognized. Others utilized dams in a destructive way. For instance, in 385-384 BC the Spartans released water from a dam to destroy a downstream city (Schnitter 1994), while Vikings used dam release to halt enemies (Sturlasson Unknown). Over the ages dams have also been constructed for:

- Mining
- Log running
- Mills (water wheels)
- Hydropower
- Ice production
- Leisure activities
- Sediment control

The development of dam technology up to the present is further described by Schnitter (1994). The World Register of Dams held by the International Commission on Large Dams (ICOLD) contained data for 25 410 large dams (height above foundation not less than 15 meters) in 1998, but according to reports from the member countries the total number of dams in operation was 41 413 (ICOLD 1998b). This number was updated to approximately 45 000 by the World Commission on Dams in November 2000 (WCD 2000). According to ICOLD, globally most dams are built for irrigation, while hydropower and water supply take the second and third places. The most common types are earth dams (64%), with gravity (19%) and rockfill dams (8%) following.

Figure 1.1 Construction of Katse Dam, Lesotho, November 1994

1.1.1 Dams in Norway

The oldest known dams in Norway still in operation were built in the 17th century for the mining industry at Kongsberg and Røros. Over time the purpose of dam construction as well as the type of dams have changed, and during the last 100 years the primary cause for dam construction has been to serve the hydropower industry. The Norwegian Water Resources and Energy Directorate (NVE) has a dam register containing data for all dams under governmental supervision, roughly this embraces those dams with a reservoir volume not less than 500 000 m^3 or a height not less than four meters or both. The register shows that the most intense construction period was between 1950 and 1989, which runs more or less parallel to the golden era of hydropower development (Jensen 1995). Before 1920 the dominant dam-type was the masonry dam, afterwards concrete dams became more and more common (Svendsen 1992). Concrete dams are still the leading type (Molkersrød and Konow 2001), even though many of the largest are rockfill dams. Molkersrød (1995) gives a description of the development of Norwegian dam engineering technology and practice. Today more than 2 500 dams are registered in the NVE database. About 335 of these are large dams (Lindland 2001), according to the ICOLD definition.

1.1.2 Dams as a hazard to downstream society

History has shown that dam failures can cause major damage downstream. ICOLD has prepared a statistical analysis on dam failures from all over the world (ICOLD 1995) as a follow-up of earlier reports "Lessons from Dam Incidents" (ICOLD 1999) and "Deterioration of Dams and Reservoirs" (ICOLD 1984). The definition of "failure" used in the ICOLD analysis is a:
"Collapse or movement of part of a dam or its foundation, so that the dam cannot retain water. In general, a failure results in the release of large quantities of water, imposing risks on the people or property downstream".
One important omission of this analysis of dam failures is data from China due to a data discrepancy, which would have given a false image of the situation in the rest of the world. It is also worth noting that the different national committees may have interpreted the definition of failure and the questions given in the questionnaire in slightly different ways. Some of the conclusions of the statistical analysis are that most dam failures occurred in the first year of operation and involved small dams and that the highest failure rate is found in dams built in the period 1910-1920. The most common causes of failure with respect to dam types are overtopping of embankment and masonry dams and foundation problems for concrete dams.

There have been few serious dam incidents in Norway compared to other countries. Norway has also been fortunate in not having any failures amongst the largest dams. There are no Norwegian data in the statistics on failure of large dams (h>15 m) at all (ICOLD 1995). Nevertheless, there is no reason to ignore the dam safety issue. Failures of small dams have resulted in approximately ten fatalities over the last century. In fact, there is one dam failure each year on average (Svendsen 1995), causing damage of differing degrees to land and property. One of the last failures of significance was the Roppa Dam (Figure 1.2) in Gausdal on 17 May 1976 during first filling of the reservoir (RL 1977). The embankment dam was completed in September 1975 and the reservoir volume was 3.2 million m^3. The failure caused no fatalities, probably because most of the community was celebrating Constitution Day in Gausdal. In addition, and by coincidence, the dam attendant made an extra tour to the dam at an early stage of the failure and managed to warn the few people who were in imminent danger. The cause of failure was probably either leakage along bottom outlet due to insufficient compaction or ice embedded in the soil zone around the culvert. The failure at Roppa Dam lead to increased interest in dam safety in Norway. The first Norwegian dam safety regulations issued in 1981 were influenced by this event (Lysne 1999).

Figure 1.2 Roppa Dam after failure (photo: Department of Hydraulic and Environmental Engineering, NTNU)

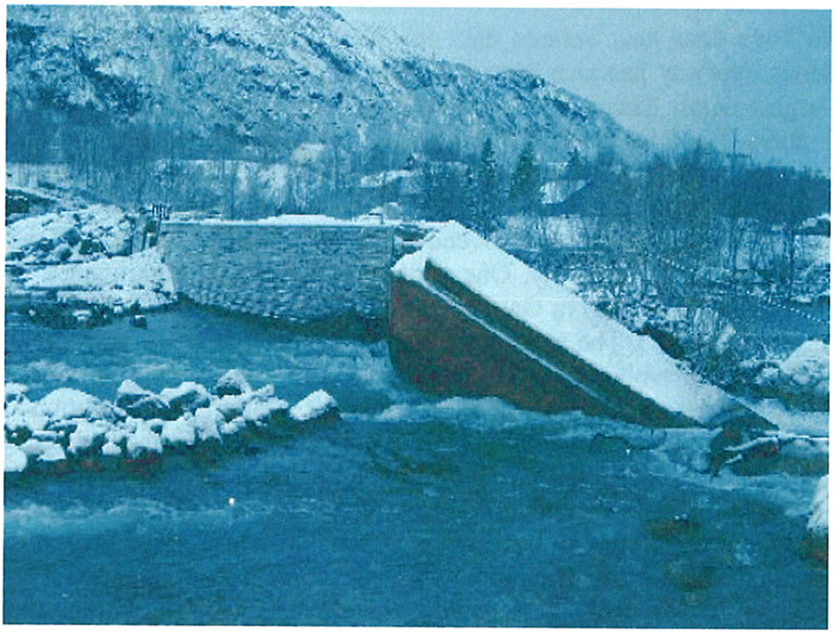


Figure 1.3 Failure of Nervatn Dam, Blokken River, 11 January 2002 (Pedersen 2002)

Further back in history, the most serious dam failure in Norway was in Trondheim during the spring flood of 1791 (Svendsen 1992). The Kobber Dam (Kobberdammen) failed and the flood wave led to the failure of two downstream dams. Thirty people in the downstream area of Ila were killed, and 6 houses and the mill Ihlens Møllebrug were completely destroyed. Recent failures caused by flood in Norway include Tippskaret Dam in June 1995 (see Section 5.9.5) and Nervatn Dam in Blokken River basin on 11 January 2002 (Figure 1.3). The Nervatn Dam was a small concrete dam classified in the low consequence class. The failure was caused by erosion of the right abutment, which resulted in the overturning of a 20 m long section of the concrete dam (Pedersen 2002). The stop logs in the spillway had not been opened because the dam owner was too late in reacting to the increasing water level. The flood was caused by extraordinarily warm weather combined with rain (i.e. 250 mm in 4-5 days). The rainfall had an estimated return period of 200 years. The consequences were limited to damage to three downstream bridges including one main road bridge, and the loss of approximately 1 million m^3 of water (50 % of the reservoir capacity).

1.1.3 Dam safety practice in Norway

The establishment of the public Control Department for Dam Safety in 1909 (Andersen 1996) is probably one of the reasons why there have been few severe dam failures in Norway. Nowadays this department functions under the auspices of the Licensing and Supervision Department of NVE. The objective of the former Control Department was to ensure that dams and appurtenant works were designed and built according to good practice and that existing dams had a sufficient safety level. According to Nicolaisen (1998) this was done by the control and approval of plans and supervision of dams under construction and in operation.

Prior to 1981, when the first regulations on dam safety were issued (NVE 1986), supervision and control was founded on good engineering practice and standards. The new regulations emphasized the planning and construction of dams. After a couple of incidents in Sweden in 1985 and Norway in 1986, NVE realized that the regulations did not put enough emphasis on dam operation. After a preliminary study on dam risk analysis (NVE and VR 1987), a major program, the Dam Safety Project, was initiated in 1988 and ran until 1992. It investigated various aspects of dam safety such as emergency planning, clogging of spillways and ageing of concrete dams (NVE and VR 1992). The Dam Safety Project concluded that there was a general need for revision of the 1981 Dam Safety Regulations in order to include more aspects of dam operation. The project also recommended that dams should be classified with respect to their downstream hazard.

In 1992, regulations on the supervision of dams were issued which introduced the internal control system as a tool for safety management in the operation of dams. This system is meant to ensure that dam owners comply with the legal requirements concerning dam safety. Important elements are among others (Molkersrød and Konow 2001):

- Inspection program
- Reassessment of dam safety (every 3rd main inspection)
- Emergency action plan

After 1993, NVE changed their focus from regular dam inspections to regular audits of the internal control systems including interviews with personnel and inspections of selected dams. Along with the development of the internal control system, NVE introduced other practices such as regular reassessments of dams, approval of qualified personnel and requirements for emergency planning in the case of natural events. Many are, in fact, recommendations given by the Dam Safety Project. However, often these had weak support in existing laws and regulations. It became apparent that there was a general need to incorporate new knowledge and technology into the regulations and guidelines, as well as an overall revision of the legal framework for dam safety (Svendsen and Grøttå 1995).

New regulations for dam safety were issued in 2001, and they replace both the previous regulations from 1981 and 1992. The regulations now give functional requirements instead of detailed technical requirements. Thus, there is now a need for the development of technical guidelines. Some guidelines are already available in the Safety Handbook issued by NVE, but most of these will be revised and new ones will be added. The new regulations focus more on the operation, maintenance and upgrading of existing dams than the previous regulations. The dams (and thereby the dam owner organizations) are divided into three consequence classes, and the requirements are adjusted to each consequence class. The new regulations also give NVE the legal authority to require risk analyses and emergency plans, along with other requirements, which previously had weak legislative support.

Along with the developments in dam safety management described above, NVE and the Norwegian Electricity Industry Association (EBL-Kompetanse) have both striven to maintain and upgrade competence in dam safety. Dam safety courses at different levels are regularly given as a result of cooperation between NVE, NTNU and EBL-Kompetanse. Some are compulsory in order to receive approval as chartered dam engineer (VTA) or qualified consultant. A technical forum for approved personnel (VTF) has also been established which offers technical seminars at regular intervals. The technical seminars cover topics of current interest, and allow the exchange of experience between dam owners. Naturally, VTF also functions as a network for professionals working with dam safety in Norway.

1.2 Objectives and scope

Design floods and coherent design water levels have traditionally received much attention during the design and reassessment of dams. Some possible deficiencies in the traditional approach have been identified. It is believed that dam safety assessors should pay more attention to factors such as flood duration, geographical extent and secondary effects than they do today. The combined effect of these factors is probably underestimated. Dam safety reassessments also tend to focus on single dams, while floods often affect one or more river basins. The complexity of floods is difficult to fit within the framework of traditional risk analyses currently used in many dam safety reassessments. Flood events may also be problematic to assess due to lack of experience. These various deficiencies influence the quality of emergency planning and exercises, both of which are fundamental elements in present dam safety management systems.

The main objective of this thesis has been to evaluate the complexity of severe floods and their possible effects on dam safety. As risk analysis and emergency planning are rather new elements within dam safety management in Norway, the status for these fields is of interest. Furthermore, an investigation of historic and recent floods has been carried out to improve understanding of floods. In order to increase the realism during emergency exercises and safety analyses, a method for creating flood scenarios based on real events has been developed. The following activities have been central to the study:

- Evaluating present practices for risk analysis and emergency planning
- Surveying the status of emergency planning for dams in Norway
- Extending the knowledge base of flood events
- Developing a method for creating flood scenarios
- Evaluating methods for analysis of flood scenarios
- Creating a realistic flood scenario for the Vinstra River basin based on the well known 1789-flood (Storofsen)

This thesis focuses on dam owner responsibilities during floods. Issues such as structural safety, downstream valley flood plain management or flood handling which are under the responsibility of local authorities and other parties are not emphasized. Some of these issues have already been covered in earlier studies, such as a recent report on infrastructure vulnerability to major floods (Jenssen 1998), and the HYDRA-project described in Section 5.9.7. Structural safety of spillways and embankment dams is the main topic of another doctoral program at NTNU undertaken by Hilde Marie Kjellesvig.

1.3 Thesis organization

The first part of this thesis is devoted to various dam safety issues, with emphasis on floods, risk analysis and emergency planning. Chapter 2 provides an overview of some dam safety issues of special relevance for coping with severe floods. Topics covered are design flood estimation and flood risk related to dams and spillways. Chapter 3 presents a literature review and discussion on risk analysis for dams. An overview of emergency planning for dams with examples from Norway and USA is given in Chapter 4. A survey of emergency planning for dams in Norway is also presented in this chapter.

Identification of typical problems related to the operation of dams during floods has been done by means of a qualitative study of selected flood events. The study, presented in Chapter 5, also includes some extreme flood events in unregulated rivers to provide background information for assessment of the possible consequences of very rare events. Chapter 5 includes some examples of measures at dams and reservoirs done after flood events. A method for the creation of reliable flood scenarios for emergency exercises and training of dam operator staff is presented in Chapter 6. The use of scenarios for safety assessments is discussed in the same chapter, as are some examples of the use of scenarios for purposes other than increasing the safety of dams. The proposed method was tested with the Storofsen-scenario, as Storofsen is a well-known extreme flood for the Vinstra River Basin. The Vinstra case study is documented in Chapter 7.

2 ASPECTS OF FLOODS AND DAM SAFETY

2.1 Introduction

Even though dam construction has, in many cases, improved the ability to prevent flooding in downstream areas, it must not be forgotten that dams and reservoirs also introduce a new hazard to those same areas. Thus, investment in safety must be an integral part of the project costs for new dams and the maintenance costs for existing dams. According to ICOLD, a safe dam can be defined as *"a dam free of any conditions or developments that could lead to its deterioration or destruction"* (ICOLD 1987). Absolute safety, however, is not realistic for any dam, as absolute safety cannot be guaranteed for any activity or structure in our society. Thus, emphasis must be put on ensuring a tolerable risk level by means of cost-effective structural and non-structural risk reduction measures.

Public supervision of and legislation on dam safety is a good assurance against dam failure. Equally important is the way in which the dam owner emphasizes the safety issue and safety management is practiced. Bowles et al. (1997) suggest that a dam safety management program for a high hazard dam should include:

- Risk assessment for evaluation of existing dams and alternative remedial actions
- An emergency warning system and action plan
- A monitoring and surveillance program
- A well-trained operations and maintenance staff
- A well-planned maintenance program
- Routine inspections, periodic in-depth inspections and comprehensive dam safety reviews
- An effective public consultation program

Successful dam safety management also depends on dam owners' knowledge about their own dams, their will to learn from experience gained from previous adverse incidents and their interest in safety issues in general. Dam safety includes a variety of topics and disciplines as indicated by the list above; some of them will be addressed further in the following sections.

Dams exposed to floods of the same magnitude as the design flood are, of course, vulnerable to any additional loadings. However, floods that are considerably smaller than the estimated design flood may also pose a hazard to dams. The effects of floods and prevailing weather conditions may cause several problems to dam operation. In particular gated spillways have proven to be vulnerable to common cause failures (see Section 2.8). The occurrence of flood hazards will further be influenced by for example catchment characteristics, infrastructure and administrative systems.

Aspects of floods with respect to dam operation have been discussed at several conferences including:

- ICOLD 16th Congress on Large Dams (Q.63), San Fransisco, USA 1988
- Dams and Extreme Floods (topic B), Granada, Spain 1992
- New Trends and Guidelines on Dam Safety (topic 3), Barcelona, Spain 1998
- ICOLD 20th Congress on Large Dams (Q.79), Beijing, China 2000
- Dams in a European Context (topic B), Geiranger, Norway 2001

Interesting papers on floods and dam operation are, of course, not limited to the conference proceedings of the events listed above.

2.2 Design flood for dams

2.2.1 Selection of design flood

Dams are designed to pass a certain design flood safely without being damaged. Selection of design flood is in many cases governed by legal requirements, and a criterion for selection may be according to the consequence class of the dam. ICOLD has reviewed the design flood issue worldwide, which is reported in bulletin 82 “Selection of Design Flood - Current Methods" (ICOLD 1992). The review also covers methods for calculation of the design flood and case histories of accidents caused by floods.

Selection of the design flood is a difficult matter and there are several possible approaches as discussed by Cassidy (1994), Fahlbusch (1999) and Fridolf (2001). The design flood can be independent of dam characteristics, based on hazard classification or on risk assessment indicating an optimum design flood (that is one that would result in the minimum annual cost). Most existing guidelines recommend that the return period for design floods should be chosen in terms of dam height, reservoir size and an evaluation of the downstream hazard (Cassidy 1994). For dams posing a threat to life, most regulatory agencies recommend that the design flood be equal to the Probable Maximum Flood (PMF) or another flood with a very high return period, for example a 10 000-year flood ($Q_{10\,000}$) or a 1000-year flood (Q_{1000}). In some countries two floods are defined; for spillway design and dam safety control, respectively:

- The "safety check flood" often made equal to the PMF. This flood must be bypassed safely without causing dam failure, but some damage to the dam may be accepted.
- The "design flood" often made equal to a percentage of the PMF or a flood with a specific return period. This flood represents an inflow, which must be discharged under normal conditions with a safety margin provided by the freeboard. The design flood is the basis for the design of spillway and outlet works.

For the construction period, there is a separate design flood for the diversion works, often in the magnitude of a 20- or 30-year flood. This practice of using significantly lower floods as design floods for diversion works than for spillways is disputable. Many dams have experienced far more severe floods during construction than the design flood for the diversion works (Fahlbusch 1999).

Norway follows the practice of using the PMF as the safety check flood and Q_{1000} as the design flood for high hazard dams, see Table 2.1.

Table 2.1 Design flood requirements according to revised Norwegian dam safety regulation (Molkersrød and Konow 2001)

DAM HAZARD CLASSIFICATION	DESIGN FLOOD	SAFETY CHECK FLOOD
HIGH	Q_{1000}	PMF
SIGNIFICANT (MEDIUM)	Q_{1000}	PMF or 1,5 x Q_{1000}
LOW	Q_{500}	-

The Norwegian requirement for high hazard dams seems to be in line with international practice as presented in Table 2.2, while the Norwegian requirements for low hazard dams may be on the strict side.

Table 2.2 Common practice for selection of design flood around the world according to Berga (1998)

DAM HAZARD CATEGORY	LOSS OF LIFE	ECONOMIC, SOCIAL, ENVIRONMENTAL & POLITICAL IMPACTS	DESIGN FLOOD	SAFETY CHECK FLOOD
HIGH	> N	Excessive	%PMF or $Q_{1000} - Q_{5000}$	PMF or $Q_{5000} - Q_{10000}$
SIGNIFICANT	0 - N	Significant	%PMF or $Q_{500} - Q_{1000}$ or ERA	%PMF or $Q_{1000} - Q_{5000}$ or ERA
LOW	0	Minimal	Q_{100}	$Q_{100} - Q_{150}$

Selection of an optimum design flood through economic risk assessment (ERA) implies estimation of the probability and consequences of a conceivable dam failure and determination of a design flood through an iterative process where costs and risks are evaluated. The method is complex and may therefore be expensive. One of the main objections to a risk assessment approach, however, is the problem of putting a monetary value on environmental affects and human lives, as exemplified by Cassidy (1994). In addition, input data for risk analyses are often uncertain, such as the probability of the floods considered and probable damage. Fridolf (2001) has compared the Swedish guidelines for dam design floods to 15 other countries including Norway. According to Fridolf, only a few countries have so far adopted risk assessment principles in the determination of the spillway design flood.

2.2.2 Methods for estimation of design flood and PMF

Methods for the estimation of floods based on empirical rules, for example doubling of the largest peak flow recorded at the dam site, have been much used around the world but are not very common anymore (Fridolf 2001). Rather, present practice is to use frequency analyses or hydrological models. Hydrological models are, for example, used to estimate the PMF, even though each country has its own approach (Harlin 1992a). Estimation of spillway design floods different from PMF, however, must include some kind of flood frequency analyses either based on runoff records or a combination of rainfall and runoff records. Some kind of frequency analysis must also be included in the basis for selection of design flood by using risk assessment.

Killingtveit and Sælthun (1995) divide flood estimation methods into two categories: those related to the analysis of flows (flood frequency analyses), and those related to the analysis of rainfall (rainfall/runoff analyses). Flood frequency methods can be divided further into two sub-categories: single site or regional analyses. Both methods are based on flow records alone. The alternatives to flood frequency methods, rainfall/runoff methods, are either based on combined analysis of rainfall and runoff or on transformation of rainfall records to flood estimates by use of hydrological models. All methods can be denoted as probabilistic except those methods using hydrological models, which are deterministic.

All methods, whether probabilistic or deterministic, have their advantages and disadvantages as described by, for example, Fridolf (2001) and Killingtveit and Sælthun (1995). The frequency methods are emphasized as being simple to apply and able to provide a return period. The disadvantages regarding extreme flood estimation, however, are that runoff observations have to be extrapolated far beyond the observation period, and that different distribution functions give different results. The flood records used for frequency analyses are in most cases limited to a time period of 50 to 100 years; thus, extrapolation to a design flood with a 1000-year return period is naturally uncertain. Some of the advantages of hydrological models compared to frequency analyses are that they are easier to adjust to changes, can be based on the actual properties of the catchment, and can be calibrated against available data. There are also several disadvantages, among others, that there is no return period connected to the estimated design flood or PMF. A thorough discussion of hydrological models with an emphasis on uncertainties encountered in the simulation of extreme floods and long-term scenario simulations is given in Bergström (1991). One of the aspects emphasized is the need for control of the results against observations. However, for estimation of extreme events there are normally no data at hand for control of the models and a combination of uncertainties has to be considered, for example, that the hydrological model will be run with data being outside the range of those used for calibration. Harlin (1992b) indicates that the uncertainty in design flood estimations, using the HBV-model and following Swedish guidelines, may be in the range of ± 20%.

Risk assessment can be used as a principle for the selection of the design flood. Independently of how the design flood is selected there is also an increasing interest in risk analysis as a tool for dam safety management. Consequently, there is a general need for assigning probabilities to extreme floods. The relationship between return period (T), and probability of exceedance (P) over a period of N years is given as (Killingtveit and Sælthun 1995):

$$P = 1 - \left(\frac{T-1}{T}\right)^N \qquad (2\text{-}1)$$

Thus, for a structure with a design flood of return period (T) of 1000 years, the probability (P) is 10% (0.1) of a flood exceeding the design flood within a lifetime (N) of 100 years (Table 2.3). The return period reflects the average interval of time, or number of years, within which an event will be equal or exceeded (Johansson 1984).

Table 2.3 Probability in percent as function of return period (T) and period length (N)

RETURN PERIOD (T)	LENGTH OF PERIOD (N)				
	10 years	50 years	100 years	200 years	500 years
10 years	65%	99%	100%	100%	100%
50 years	18%	64%	87%	98%	100%
100 years	10%	40%	63%	87%	99%
200 years	5%	22%	39%	63%	92%
500 years	2%	10%	18%	33%	63%
1000 years	1%	5%	10%	18%	39%

The problem of assigning probabilities to extreme hydrological events by standard frequency analyses has been discussed by Klemes (1993). Klemes defines the standard approach as the fitting of mathematical probability distribution models to ordered sequences of recorded events, for example flood peak discharges, and extrapolating the tails of these models to very low exceedance probabilities. Instead of putting effort into curve fitting he calls for a different approach where synthetic distribution curves are constructed based on more information on the physics of the phenomena involved (a combinatorial approach). Consideration is given to the fact that some components have physically imposed upper limits, something that may not be obvious in a standard frequency analysis of compound events. An example given by Klemes (1993) for Coquitlam Lake in British Columbia, Canada,show the estimation of annual maximum of daily precipitation with exceedance probabilities down to the order of 10^{-5}. Further studies, obviously based on Klemes' ideas, are presented by Salmon et al. (1997).

Another method currently investigated by the US Bureau of Reclamation (USBR) is to use historical floods and paleofloods to assist in assigning probabilities to extreme floods (England and Levish 2000). Known historical floods and paleofloods (indicating stages of non-exceedance) are included in the flood record and can thereby help defining the form of the frequency curve. According to Reed (1999) an historical flood can be defined as a flood preceding the gauged period of record from which there is contemporary information, such as newspaper reports or flood marks. More extreme flood levels and/or velocities deduced from geo-morphological data are referred to as paleoflood data. Paleoflood studies comprise sampling, dating and interpretation of old or ancient floodplain deposits. By studying several cross-sections along a limited river stretch, the paleoflood discharge can be calculated by the means of hydraulic computations. Paleoflood studies are highly specialized tasks, which have a tradition in the southwestern part of USA (Reed 1999). Paleoflood studies for mountain floods have also been conducted in Spain as reported in Rico et al. (2001).

2.2.3 PMF and design flood estimation in Norway

After the dam safety regulations were issued in 1981, there was a need for updating design flood and PMF estimation for most Norwegian dams. Since then, flood estimations have been carried out for more than 800 dams, sometimes followed by upgrading of the dam structure or spillway (Pettersson 1998). The PMF is calculated by use of rainfall/runoff models on the basis of estimates of probable maximum precipitation (PMP). The PMP is estimated as a function of the precipitation with a 5-year return period and growth curves. This method was originally developed in the UK but has been adjusted to Norwegian conditions. In most cases a snowmelt contribution should be added to the PMF. The design flood, on the other hand, has to be estimated with some kind of frequency analysis. This is done, either by doing a single site analysis, or by doing a regional analysis. A regional analysis for Norway was prepared in 1978 and updated in 1997 (Sælthun 1997). The updated version introduces a new classification of regions and new estimates for the relationship between mean annual floods and the 1000-year floods. When flow records are insufficient or not available, the design flood can be calculated using rainfall/runoff models and estimates of precipitation events with a 1000-year return period. If possible, the results from this analysis are compared to calculated floods in similar catchments in the same area.

Several hydrological models may be appropriate for rainfall/runoff modeling. One that has been used all over the world is the Swedish HBV-model. The rainfall/runoff model most often used for design flood and PMF calculations in Norway, the PQFLOM/PQRUT-model (hereafter referred to as PQRUT), is a simplified version of the HBV-model. Floods calculated by means of the HBV-model with 1000 years precipitation (without snow melt contribution) are in good agreement with the 1000-year autumn floods calculated by the means of frequency analyses according to Beldring et al. (1989). However, for catchments dominated by spring floods (with a significant snow melt contribution), the hydrological model produces flood values that are too low. Beldring et al. (1989) conclude that for catchments with poor data, regional analyses can be a good support in design flood estimations.

There have been objections to the use of the simplified PQRUT, particularly for large catchments. Erichsen et al. (1999) have tested different versions of PQRUT against a complete version of the HBV-model and found that the results differed significantly. The test comprised design flood and PMF calculations for the Alta River at Masi (catchment area 5627 km^2) and the Suldalslågen River at Suldalsosen (catchment area 1305 km^2). Three different PQRUT-models, a complete version of the HBV-model and flood frequency analysis (for the design flood) were compared. Floods calculated by the most commonly used PQRUT-model were in both cases much larger than floods calculated by any of the other methods. Their conclusion was that even though the results are very clear, more tests should be carried out. As a follow-up, EBL-Kompetanse has initiated a new project recently emphasizing the need for better flood estimation methods (Lundquist 2001b).

For Norwegian dams in the high and medium consequence classes, the design flood is set to Q_{1000}, as shown in Table 2.1. This is by definition "*the inflow flood, with a return period of 1000 years, that results in the highest water level in the reservoir given particular conditions for operation of spillways and initial reservoir level*" (NVE 2001). As the water level in the reservoir is normally allowed to rise above the highest regulated water level (HRWL) during floods, the outflow flood from the reservoir will be damped compared to the inflow flood. For large reservoirs, the flood volume and duration will play an important role in the determination of the design flood hydrograph, while the peak of the inflow flood is normally more important than duration for smaller reservoirs. For routing through the reservoir, one of the general requirements is that initial water stage in the reservoir be set to the HRWL. Transfer tunnels for water into the catchment are normally considered open, while transfer tunnels out of the catchment are considered closed. Further description and practical recommendations for flood estimation based on the Norwegian procedures are given by Killingtveit and Sælthun (1995) and Pettersson (1998).

New guidelines on flood estimation have been prepared and will probably be issued in the near future (NVE 2001; Pettersson 2001). These require that flood estimations be classified with respect to uncertainty based on an evaluation of available data. In addition, sensitivity analyses of the flood estimations are recommended. Otherwise, there are no significant changes with respect to methods for estimation of design floods and PMF in the revised regulations and guidelines. The new legislation will therefore not trigger a general revision of design flood and PMF estimation for dams in Norway.

2.3 Flood and catchment characteristics

2.3.1 Seasonal variations in Norway

In Norway where most dams are built for hydropower, consumption of water is usually highest during winter, when there is normally very little inflow to the reservoirs due to precipitation falling as snow. Thus, the large reservoirs are mostly empty during late winter, which is a benefit when there are severe spring floods. On the other hand, the reservoirs are filled during summer and autumn, and offer very little storage capacity for autumn floods. There are three main causes of natural floods: snowmelt; rain on snow; and rain. Autumn floods are caused by heavy rain and saturated soil, sometimes in combination with melting of newly fallen snow. Spring floods are a result of snowmelt and may be increased due to rain or melt water flowing over frozen ground. Spring floods tend to have longer durations than autumn floods, but the autumn flood in 2000 documented in Section 5.12 shows that there are exceptions. In coastal areas there may be no seasonal distinction between spring floods and autumn floods. Floods appear at any time of year, but are least likely during summer, which is most often a low runoff season. Some Norwegian river basins also contain glaciers. Glacial runoff can be dominant in catchments with glaciers covering only a small percentage of the area. Characteristic for these catchments are floods during summer (Beldring et al. 1989; Sælthun 1997).

2.3.2 Weather conditions

Flood events will appear in different ways according to prevailing weather conditions. Both thunderstorms and strong winds may affect the eventual consequences of a flood. Even though it is not a weather phenomenon as such, the total or partial absence of daylight in Norway and other countries at high latitudes during winter and late autumn may also increase the effects of wet and windy weather. Lightning strike is a possible threat to dam operation if power supply and communication systems are interrupted. Wind may cause extensive damage to forest, and fallen trees may block access roads and damage power lines. Wind or thunderstorms or both may, furthermore, stop or restrict the use of helicopters to remote locations. Wind can also generate waves in reservoirs; wind setup and seiches (standing waves). Wind setup is increased water level due to the movement of water masses caused by constant wind from one direction. Seiches are rhythmic oscillations on the water surface due to weather phenomena or rapid changes in reservoir outflow.

Waves are, to a great extent, accounted for in dam design, at least those dams designed or rehabilitated according to the Norwegian dam safety regulations of 1981. An investigation at the Aursjøen Reservoir showed no obvious correlation between high precipitation and high waves towards the dam driven by the prevailing wind direction. However, since high water levels may endure for some time, any wind direction and wave condition may prevail. High water levels and strong winds towards the dam should therefore be considered to act simultaneously (Tørum 1994). As part of the recent revision of the Norwegian dam safety regulations, a study of design wind, design waves and rock sizes in the upstream protective layer has been performed by SINTEF (Tørum 1998). The study included a survey of damage caused by waves on 25 Norwegian dams, and one of the conclusions, among others, was that most dams built according to the regulations were "over-designed", that is their ability to withstand waves is very good.

2.3.3 The influence of catchment characteristics

Topography, geology and vegetation in the catchment will have an influence on runoff, erosion, landslides, rockslides and rock falls during a rain-flood event. Steep slopes, saturated or frozen ground and/or hard smooth ground surfaces will contribute to rapid runoff, as was the case with the 1985 Ore River flood, Sweden (see Section 5.6). Erosion may occur at the riverbanks damaging; for example, flood protection structures and bridge piers. The accident at the alluvial fan of Moksa River, Norway, in 1995 is an example of the way in which erosion can cause severe damage during floods (Section 5.9.4). Erosion in areas with quick clay is also a known hazard. In reservoirs wave actions can erode material from the surrounding slopes. Erosion may trigger landslides into reservoirs and rivers (due to the removal of stabilizing materials at the base of the slope), but landslides may also be initiated by heavy rain or by high pore pressure following quick drawing down of a reservoir. When the 1995 flood

(Section 5.9) was on the decline, discharge through Svanfoss Dam in the Vorma River (which regulates lake Mjøsa) had to be reduced gradually to avoid any clay-slides into the river. Such a slide blocked this river for 111 days in 1795, causing the water level in lake Mjøsa to increase by 8 m (Lundquist et al. 1996).

All changes in the stability of the slope will influence the probability of sliding, thus attention should be paid when, for example, deposits or road fills are added to the top of steep slopes. It should be kept in mind that slopes may appear stable for a long time after mass deposits or filling, suddenly becoming unstable during a heavy rainstorm or due to water infiltration from other sources. Obstruction of access roads and damage to other infrastructure are easily seen effects of landslides, which may have an effect on dam operation during floods. Bolt et al. (1975), and Singh (1996) describe the various causes and mechanisms of slides, as well as flood hazards in general. Bolt emphasizes geological hazards and Singh the hydrological aspects of various natural disasters.

Overland flooding in normally dry areas is naturally a problem during severe floods. The effect on dam operation is mostly connected to the accessibility of gates at the dam site or between the dam site and other central places. Severe floods are so rare that dam personnel may not be aware of potential floodplains or potential new watercourses created by small creeks growing into rivers. Inundation mapping can be a useful reminder of where flooding may occur over flat areas, while flooding in steeper areas, as "new" creeks and rivers develop, may be more difficult to perceive. Scars in the landscape and descriptions of previous severe floods can give a hint in this context. Type and density of vegetation may also determine whether overland flooding will lead to erosion. Finally, it is also worth mentioning that sediment transport caused by erosion during floods may be a problem in itself; mainly due to deposition of sediments in lower floodplains. Filling of reservoirs thereby decreasing their capacity or the possible blocking of intakes may also be hazardous in some cases. An example of the way in which the hazard associated with transported sediments has been mitigated is the construction of Ula Dam in 1877. The objective was to protect the floodplains at the confluence with the Gudbrandsdalslågen River northeast of Otta (Sætren 1904). The dam was built to collect sediments in a controlled manner, before the steep Ula River enters the floodplain.

2.3.4 Floods caused by accidents or destructive actions

Natural floods are caused by rain or snowmelt. Independent of these, natural disasters may also generate floods or flood waves. Further more, natural floods can be exacerbated by accidents or destructive actions thereby causing extra strain on the river system. These floods may for example occur on sunny days with generally low runoff, when a flood is least expected. The most relevant events with a potential to cause severe downstream floods are:

- Earthquakes
- Slides and rockfalls
- Jøkulhlaups (Glacier Lake Outburst Floods, GLOF)
- War and terrorism
- Failure of the dam, the spillway or the foundation
- Faulty operation of gates

Only three large dams have failed as a direct consequence of earthquakes according to ICOLD (1995), and they were all embankment dams. Earthquakes may, however, trigger landslides into reservoirs and seiches (see Section 2.3.2) in reservoirs (Bolt et al. 1975). A serious effect of slides, or rockfalls, into reservoirs is creation of surges (tsunamis). A well-known example is the disaster at Vaiont Dam, Italy, which killed 2600 people in 1963 (Jansen 1980). Steep slopes encompass the reservoir and an ancient landslide was registered at the reservoir rim. Instability of the slope was recognized prior to the disaster, and some measures were taken (lowering of lake water level and surveillance). In the spring of 1963 the slope appeared to have stabilized and lake water level was raised. Then, after a period of heavy rain and water storage recharge in the rock masses, there was a tremendous slide into the reservoir on 9 October 1963. The rock masses created a surge overtopping the dam and causing a flood wave in the downstream valley.

In mountain regions, rockfalls are naturally hazardous, and the western part of Norway is a typical hazard area. Ramnefjell in Loen, West-Norway, is a notorious mountain that has caused devastating surges in Lake Loenvatn (Figure 2.1). The most extensive rockfall, in 1936, caused a 70 m high surge to buildup causing 74 fatalities, while 61 lives were lost in the disaster of 1905 (Bruaset 1996). Another example is the rockfall in 1934 in Tafjord, to the north of Loen, which also caused many deaths. There are no reports of rockfalls into reservoirs in Norway, but as far as the author knows, there is at least one reservoir where monitoring of a large block is carried out due to potential rockfall.

GLOF's (Glacier Lake Outburst Floods) or jøkulhlaups are large floods caused by the sudden drainage of glacier-dammed lakes or natural moraine dams, which obviously pose a hazard to any downstream development. These phenomena are described further in Section 2.5.

During World War II the Möhne Dam in Germany was bombed and destroyed causing 1200 deaths (Rettemeier et al. 2001). Apart from the imminent danger to the downstream population caused by bombing, severe damage to infrastructure may be a reason for bombing. Apart from bombing, wartime and terrorist actions may include blasting the dam by placing explosives on it, as was the case at Peruca Dam in 1993, during the Patriotic War in Croatia (Rupcic 1997). The destruction of the Peruca Dam could have caused a catastrophic flood destroying downstream settlements, dams and hydropower plants. The damage caused to the embankment dam was extensive, but the lowering of water level through the bottom outlet and dumping of clayey gravel on the damaged dam crest sections prevented a complete dam failure.

Natural disasters and war may both result in failure of downstream dams. However, dam failures can also occur due to deficiencies in the dam structure or foundation. An overview of dam failures is, among others, given by Jansen (1980). Other reports of failures of large dams can be found in various ICOLD publications such as "Lessons from dam incidents" (ICOLD 1999) and the report from the 19th Congress on Large Dams – Q.75 "Incidents and failures of dams". A flood caused by the failure of a large dam will appear as a flood wave with high flow velocity. In addition, when the failure is sudden (such as for the failure of Malpasset arch dam, Figure 2.2) there will be little warning, which evidently increases the downstream risk.

Failure or incorrect operation of large spillway gates and failures of small dams may also result in devastating damage. The failure of the Lawn Lake embankment dam in the Rocky Mountains, USA, in 1982 (Figure 2.3) is a well-documented example of how much damage a failure of a small dam can cause (Jarrett and Costa 1986). The cause of failure was probably piping along the outlet pipe embedded in the dam body. Impounded water at the time of failure reached a height of 7.3 m. The reservoir capacity was 831 000 m^3 and the peak discharge has been estimated at 510 m^3/s. The failure caused the deaths of three people and damages reached a cost of USD 31 million. The flood-wave overtopped a 3.65 m high gravity dam at Cascade Lake, 11 km downstream of Lawn Lake. The Cascade Lake Dam was overtopped by 1.3 m before tipping over and failing.

Figure 2.1 The inner part of Lake Loenvatn with Ramnefjell to the left*.

* The talus at the foot of the mountain is partly covered by vegetation

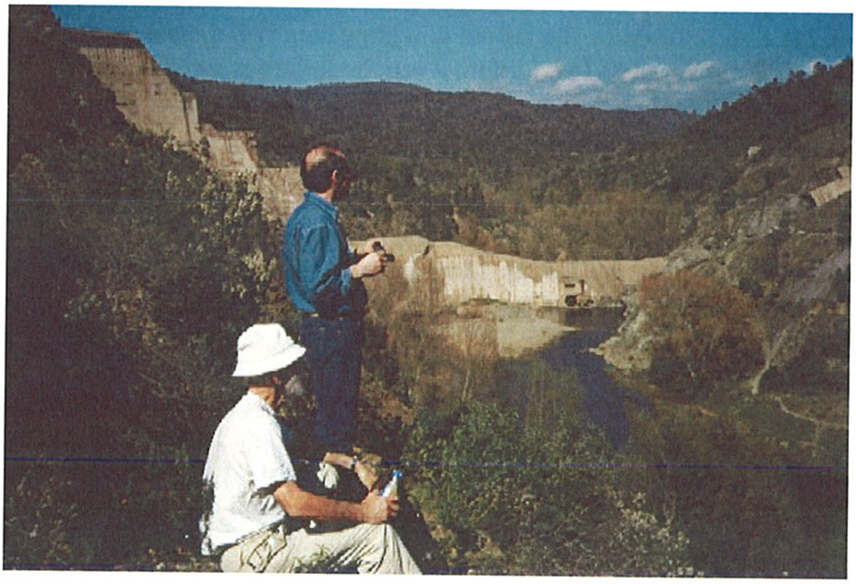


Figure 2.2 Remnants of the Malpasset Dam, 42 years after failure (photo: R. Midttømme)

The failure of Lawn Lake Dam, and subsequently Cascade Lake Dam, caused extensive damage along the river and in the town of Estes Park. The scars from the flood-wave are still visible – 20 years after the failure (Figure 2.4). An alluvial fan (now denoted Alluvial Fan) containing 279 000 m^3 of material was deposited at the confluence between Roaring River and Fall River (Figure 2.5). The alluvial fan dammed the Fall River, forming a lake upstream of the fan. Damage further downstream of Estes Park (along Big Thompson River) was prevented because the flood volume was contained in Lake Estes. Depending on characteristics of the flood wave and characteristics of any downstream dam and reservoir, dam-break flood waves obviously have the potential of causing overtopping or failure of downstream dams or both.

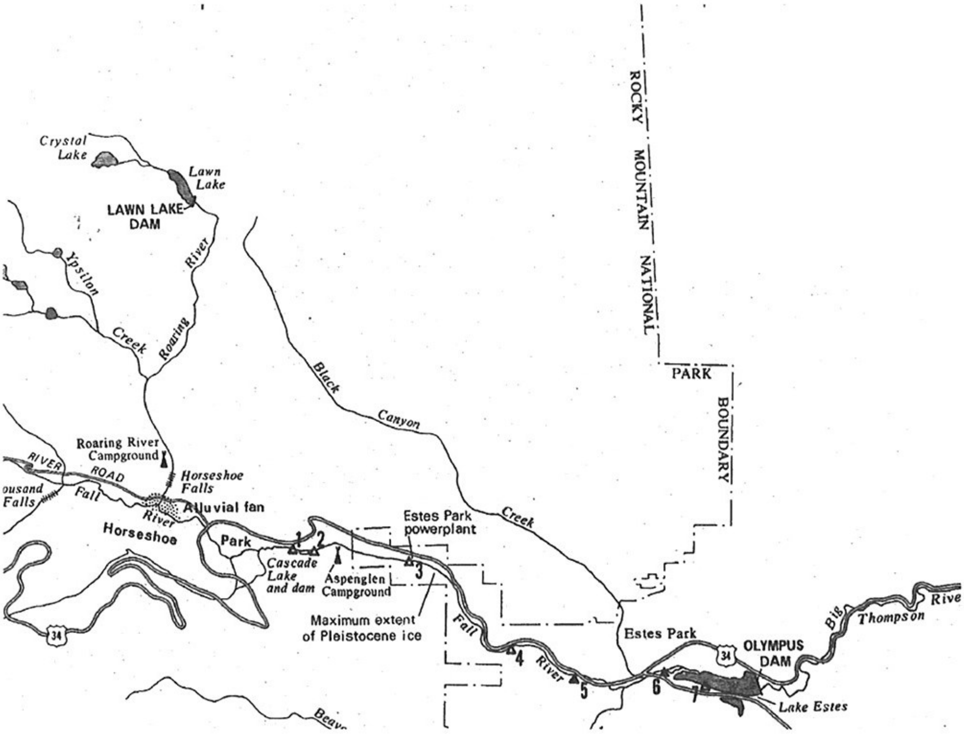


Figure 2.3 Map of Lawn Lake and the river stretch affected by the dam failure (Jarrett and Costa 1986)

Figure 2.4 Downstream reach of Roaring River (photo: T. Johnson)

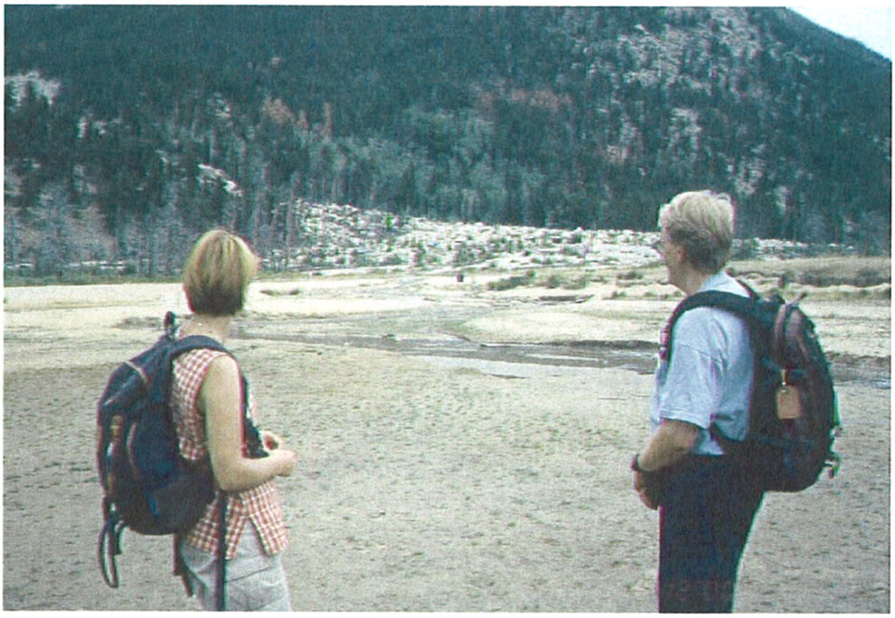


Figure 2.5 The Alluvial Fan seen from the Fall River valley (photo: T.Johnson)

2.4 Types of dams and spillways

Typical problems related to each type of dam are reflected in the ICOLD statistics on dam failures described below. A variety of dam types exist around the world, but in order to keep the overview at a general level, dam types are hereby divided into two categories:

- Concrete and masonry dams
- Embankment dams (fill dams)

Most of the large dams in the world, including most of the 330 large dams in Norway reported in World Register of Dams, fit into either one or the other of these categories (ICOLD 1998b). An investigation of European dam failures shows that there have been just as many failures of concrete/masonry dams as of embankment dams (Lempérière et al. 2001). Out of a total of 34 dam failures 14 occurred during floods, and 11 of these were embankment dams. Within the sub-categories of concrete/masonry dams, arch dams and gravity dams have the best performance. Lempérière et al. also give an overview of typical problems related to different dam types and spillways as well as recommendations for improving safety with low cost methods. Lempérière (1999) presents a similar overview of the causes of dam failures for all dams, except Chinese, in a study of application of risk analysis (Table 2.4). Out of a total of 204 dam failures with 17 000 fatalities, 89 failures (corresponding to 8 600 fatalities) occurred during floods.

Failures of concrete and masonry dams are sudden, while failures of embankment dams normally take hours to develop. However, failures of embankment dams caused by, for example, earthquake and subsequent liquefaction may also be sudden. More detailed insights into the topic are provided in textbooks, such as “Dams and Public Safety” (Jansen 1980), and other reference material on dams and safety. A general evaluation of how floods influence dam safety is presented in ICOLD bulletin no.108 “Cost of flood control in dams” (ICOLD 1997). Even though most emphasis is put on costs, the safety aspects of diversion of design floods and extreme floods (beyond the design flood) are also discussed. Spillways can be either controlled (usually gated) or uncontrolled (free overflow crests). Controlled spillways can further be divided into spillways controlled by reservoir water level (fuse gates, inflatable sills, siphons or gates controlled directly from influence of water level) or spillways controlled by an external energy source (usually hydraulically, electrically or manually). Bulletin no.108 reports that 28% of embankment dams and 40% of concrete dams have gated spillways and that the proportion of dams with gated spillways increases with spillway capacity. ICOLD bulletin no.99 (ICOLD 1995) concludes that insufficient spillway capacity is the most common cause of dam failure with respect to inadequate performance of auxiliary works (appurtenant structures).

Table 2.4 Failures of dams > 15 m high outside China (Lempérière 1999)

NUMBER OF:	Masonry gravity dams	Concrete gravity dams	Arch dams	Buttress + multiple arch dams	Fill dams	Gates/ reserv.	Total failures	Lives lost
Dams	700	3000	1000	500	12000			
Failures	18	7	4	9	159	7	204	17000
CAUSES:								
Flood during construction					21		21	1300
Flood during operation	7	1	1		59		68	7300
Upstream dambreak wave	2				4		6	1000
Earthquakes					3		3	
War	2	2			2		6	1300
First filling	6	3	3	7	29	4	52	5500
Ageing	1	1		2	31	3	38	600
Not classified					10		10	

2.4.1 Spillways

Spillways and their importance to dam safety during floods were discussed recently at Q.79, the 20th ICOLD Congress on Large Dams in Beijing, 2000. The General Report from Q.79 provides a good overview of the issue (Cassidy 2000). One paper of particular relevance to safe operation of spillways during floods came from the French Committee on Large Dams (Bister and Delliou 2000). In it, new guidelines are given which emphasize the assessment of spillway safety and surveillance of spillways. Functional aspects of various spillway solutions, and recommendations on safe passage of extreme floods, were also discussed recently by Kjellesvig and Midttømme (2001). The main conclusion given is to have redundancy in spillway systems to cope with unforeseen problems occurring when spillways must be operational, that is during or immediately prior to a flood. A case study of damage to spillways (Kjellesvig 2001) shows that many spillways are damaged by floods, which are much less than the design floods. Recommendations to avoid intolerable damage are:

- Use good monitoring systems to discover damage at the earliest possible stage
- Establish an emergency plan for coping with any damage that may be developing
- Use several passage structures instead of relying on a single gate or chute. If possible, construct auxiliary spillways

Clogging by floating debris is obviously a threat to spillways, especially gated spillways or free overflow crests with piers on top of the crest. Debris has also been recognized as a potential hazard to spillway tunnels (Lysne 1992). In cases where debris clogs spillway gates and bridge piers on top of overflow crests, it is theoretically possible to solve the problem using chainsaws, mobile cranes and other equipment. However, where debris enters and blocks spillway tunnels, there are few, if any, possibilities to solve the problem.

Erosion and landslides into reservoirs and rivers in forested areas are often the main sources of debris, but other types of debris are also often seen during a flood. These include wastes, building materials, and sometimes even complete buildings. Research on spillway clogging became part of the Dam Safety Project in order to better understand this hazard (Section 1.1.3). Model tests were carried out at the SINTEF hydraulic laboratory in Trondheim (Godtland and Tesaker 1994). The results and recommendations from this project were related to design criteria for spillways as a function of the properties of trees and tangles of trees. An example of how these recommendations were followed up is the removal of the walking bridge and piers on the overflow crest at Vinkelfallet Dam in Oppland County (see Section 5.8).

Another example where spillway tunnel clogging was taken into consideration is the building of an additional spillway at Venemo Dam in Telemark County. The new spillway was needed as a recalculation of the design flood showed an insufficient spillway capacity. The chosen concept was a tunnel spillway with free surface flow, a constant slope in the vertical plane (max. 1:7) and a constant radius curve in the horizontal plane. This concept, with no sharp shifts in the alignment, was expected to allow the passage of potential debris from the watershed (Lysne 1992). Spillway tunnels in Norway are also vulnerable to clogging by ice (Section 2.5) and rockfalls. Extra attention should therefore be given to reservoirs with dam types or dam foundations or both which are vulnerable to overtopping, and where the only spillway is one with a tunnel transport-part (see Kjellesvig (2001) for definitions of spillway systems).

Typically, gated spillways are vulnerable to mechanical part malfunction or loss of power supply for gate operation. A detailed evaluation of the reliability of spillway gates is given in (Martinsen 1992). It should be noted that standardizing spillway gates is problematic and every gate should be evaluated separately. The Norwegian Dam Safety Regulations from 1981 stated that: *"gated spillways shall only be used when possible malfunctioning of the mechanical components will not cause unacceptable consequences with respect to overall dam safety"* (NVE 1986). This requirement, albeit with different wording, is also in the new regulations, §4-13 (OED 2001). In general, NVE has therefore been reluctant to approve the use of single gated spillways for embankment dams. Nor does NVE now approve spillways with stop logs or vertical beams, as these may be difficult to operate during a flood. Some examples of problems with spillways during floods are given in Chapter 5.

2.4.2 Concrete and masonry dams

The ICOLD statistics on dam failures (ICOLD 1995) show that foundation problems are a typical cause of failure for both concrete and masonry dams, but masonry dams are also very vulnerable to overtopping. An example of a foundation problem is the failure of the arch dam Malpasset in France (Figure 2.2), which caused 421 fatalities (Jansen 1980). For gravity dams the main problem during floods is uplift pressure due to extreme raise of the reservoir level. However, it should be noted that the statistics on failures of concrete and masonry dams reported in ICOLD Bulletin no.99 (ICOLD 1995) are based on a small sample space; less than 20 concrete dams and 20 masonry dams each, while the number of failed embankment dams exceeds 130. The small sample space reflects the fact that fewer of these have been built than other dam types.

A thorough examination of 21 failures in gravity dams (including both concrete and masonry dams) is given in ICOLD Bulletin 117 (ICOLD 2000). At least seven failures occurred during a flood (six masonry and one concrete dam). The last gravity dam to fail during a flood is the 30 m-high masonry dam at Chikkahole, India, in 1972. Bulletin 117 deals particularly with gravity dams and provides a discussion of how gravity dams can be made safer and cheaper. One of the conclusions to be drawn with respect to flood hazard is that unforeseen rises in the reservoir level must be prevented by careful and conservative estimation of floods. In addition, it is pointed out that the vulnerability to reservoir-level increases also can be mitigated by selecting dam profiles that are more robust than is usual. ICOLD Bulletin 108 "Cost of flood control in dams" (ICOLD 1997) provides recommendations for meeting the challenge of increased design flood estimates for older dams. One of the conclusions given for concrete dams is that overtopping could be acceptable if the right measures are taken. Overtopping of concrete structures during floods was discussed recently by Léger et al. (2000). Léger et al. also describe a method for the assessment of maximum allowable overtopping depths.

In Norway, some of the possible problems associated with concrete dams have been followed up by investigations and research projects, such as the investigation of the safety of the foundations of arch dams (Molkersrød 1990). Even though it was later found that the investigation had neglected new insights regarding scale-effects in rock-stability modeling, the conclusion stands that the foundations of Norwegian arch dams are considered safe. Only a few dams were re-evaluated with respect to scale-effects (Molkersrød 2002) and one of these was subsequently strengthened with long rock anchors. Regarding concrete dams, much focus over the last decade has been on alkali-aggregate reactions (AAR), see for example NVE and VR (1992). One of the problems with AAR with respect to dam safety is that AAR causes the concrete to expand, thereby reducing clearance between dam pillars and spillway gates. If this condition is unknown to the dam operator, the gate may unexpectedly get stuck during operation at a critical time, such as a major flood. A survey of damage, repair and safety of Norwegian concrete dams was recently reported in (Jensen 2001). The study shows that dams built from 1950 to 1960 seems to be the most damaged and that large dams are more damaged than small ones.

2.4.3 Embankment dams

Overtopping is one of the imminent hazards of severe floods, and is also the major cause of failure for embankment dams (ICOLD 1995). The failure of the Macchu II Dam in India is an example of how insufficient spillway capacity can cause overtopping and consequently failure. The failure occurred during the monsoon in August 1979 and was caused by an overtopping (0.6 m) of the earthfill section of the dam. It is worth mentioning that the upstream dam, Macchu I, was overtopped by 1.2 m without failing, but this was a masonry dam with no earthfill sections. The estimated peak outflow from Macchu II was 13 450 m^3/s and the design flood was originally estimated to 5663 m^3/s. Fifteen of the 18 gates of the masonry section of the dam were fully opened and the rest were partially opened. Opening of the gates were done with the aims of auxiliary power due to failure of the electrical system two days before the dam failure. The dam failure probably caused the deaths of at least 2000 people (Jansen 1980).

When looking at the ICOLD statistics for earthfill and rockfill dams respectively, there have been fewer failures of rockfill (24) than of earthfill dams (98) (ICOLD 1995). Among the 330 Norwegian large dams registered in 1998 (ICOLD 1998b), 168 were embankment dams; 164 of which were rockfill dams. Rockfill dams are most probably capable of diverting a certain amount of floodwater over the dam body itself. Investigations and theories on overtopping and other failure mechanisms of embankment dams were summarized in a recent literature study (Johansen et al. 1998). This was part of a project evaluating the Norwegian guidelines for dam break wave calculations, and one of the final conclusions was that more research into failure mechanisms of traditional Norwegian rockfill dams is necessary, preferably as large scale model tests (Ruud and Midttømme 1998). This conclusion has been followed up and an ongoing project is currently investigating the failure mechanisms in traditional Norwegian rockfill dams by means of both small and large-scale model tests (Ødemark 2001).

Apart from overtopping, waves and the actions of spilled floodwater can also be a hazard to embankment dams during floods. Waves in the reservoir can cause erosion of the upstream dam face as demonstrated at the 54 m high Akersvatn Dam in northern Norway. The upstream protection layer of the dam was eroded during a storm in September 1975. The storm lasted one day and had an estimated wind speed of 15-16 m/sec. The upstream face was designed for a wind speed of 30 m/sec. The dam was rehabilitated in 1976 whereby the affected protective layer was replaced (Enfo 1997). Another undesired incident is waves spilling over the top of the dam, thereby causing erosion of the dam crest or downstream dam face. This problem has been reported for Aursjøen Dam, (see also Section 2.3.2) the main reservoir of the Aura hydropower scheme (Johansen and Riise 2001). If the outlet part of the spillway has an unfortunate design or direction or both, diverted floodwater may also be erosive causing damage to the downstream dam toe or foundation. Kvilesteinsvatn Dam before it was upgraded is an example of a dam where this problem was present (Braathen and Holm 1988). In cases where a reassessment of an embankment dam reveals insufficient spillway capacity, overtopping of the dam to divert excessive floodwater is naturally not the preferable option. General recommendations on how to increase the discharge capacities, thereby reducing the probability of overtopping, are given in (ICOLD 1997).

2.5 Problems in cold regions

Special dam safety factors related to floods that have to be accounted for in cold regions, such as Norway, are among others lake and river ice, frozen ground and the presence of glaciers. The phenomena and their consequences are described in, for example, Ryan and Crissman (1990). Typical problems during spring floods are ice-break up, ice runs and ice-jams, as well as little or no infiltration due to frozen ground. Other problems may be blocking of normal flood paths due to extensive aufeis-formations (especially in Alaska and Siberia), or heightening of the riverbed and, consequently, of flood water levels due to anchor ice. Lia (1998) has studied ice and snow blocking of tunnels, including spillway tunnels. Lia gives an overview of typical spillway design in cold regions. Several Norwegian rockfill dams have tunnel spillways and the main concern related to ice and snow is that the spillway may be blocked at the start of the spring flood. One of the recommendations of this study was to stop cold air from entering tunnels; thus preventing leakage water from forming aufeis. In addition to insulation of the spillway tunnel (Figure 2.7), Lia also recommended snow fences, systematic site inspections during winter, roofed side channels, heating cables, grouting, improved cross section, restrictions on reservoir operation and that the location of new spillways be carefully planned.

Special attention should be paid to river basins with glaciers as these can cause severe increases in flood discharges during summer floods and early autumn floods. A typical example is the flood in the basin of the Otta River during August and September 1938 (Beldring et al. 1989), and the flood of the River Jostedøla in August 1979 (Chapter 5). In cases where reservoirs are in contact with glaciers, calving of icebergs may set up waves, which can cause overtopping of dam or flooding within the reservoir. An example from Norway is the damming of the Styggevatn and Austdalsvatn lakes (Figure 2.6).

Figure 2.6 A typical Norwegian rockfill dam, Styggevatn Dam, with Jostedal Glacier in the background (photo: Statkraft)

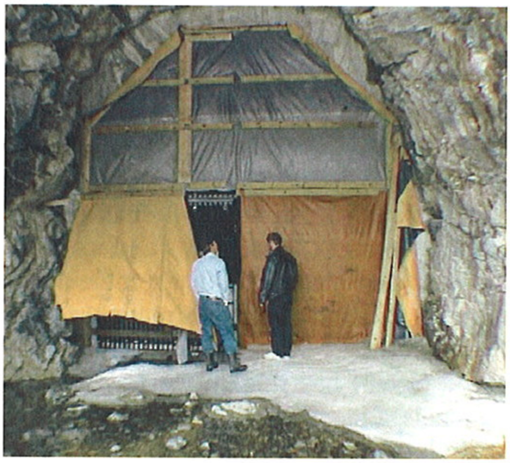


Figure 2.7 Insulation of spillway tunnel outlet at Styggevatn Dam (photo: H.M. Kjellesvig)

Figure 2.8 Styggevatn Dam and spillway, 24 June 2001 (photo: H.M. Kjellesvig)

Calving from the Austdal Glacier (a part of the Jostedal Glacier) was accounted for in the design of the dam. Concrete blocks were placed upstream of the spillway crest to protect the spillway (Figure 2.8), which is a free overflow crest with a tunnel transport section.

Another severe hazard in glaciated areas is the possibility of jøkulhlaups from glacier-dammed lakes upstream of dams. In the Himalayas, there are also examples of more or less temporary glacier lakes where the outlet is obstructed by glacial deposits (Mool 2001). Some known glacier dammed lakes in Norway located upstream of hydropower dams are Demmevatn (Rembesdalsvatn Dam), Brimkjelen (Tunsbergdalsvatn Dam) and Øvre Mjølkedalsvatn (Bygdin Dam). A study of glacier-dammed lakes in Norway was performed in the 1950s (Liestøl 1956). The situation has changed since the 1950s, as glaciers change over time. For example, Øvre Mjølkedalsvatn is no longer glacier-dammed, and there have been significant changes to Demmevatn (Elvehøy et al. 1997) and Brimkjelen (Kjøllmoen 1999). It seems that a general overview of the current hazard from glacier-dammed lakes on reservoirs and dams in Norway is lacking. NVE has recognized the need for an overall update and is presently participating in a large EU-project (GLACIORISK) with participants from Iceland and the Alp-region of Europe. The project aims to overview the potential hazards from glaciers to life and infrastructure (including reservoirs), and glacier-dammed lakes will be dealt with in particular (Kjøllmoen 2001).

2.6 Non-structural risk reduction measures

The topic of non-structural risk reduction measures with examples from several countries was covered in the recently issued ICOLD Bulletin E02 (ICOLD 2001). Even though the probability of dam failure is very small, the consequences may be catastrophic. Thus, even for dams considered to be acceptably safe, dam owners should consider a broad range of risk reduction measures. The proposed risk reduction measures in the ICOLD bulletin are:

- Risk assessment for identification of appropriate and cost-effective measures
- Training of personnel involved in the operation, monitoring and evaluation of dams
- Structural performance monitoring (surveillance)
- Emergency planning to reduce the consequences of any undesired event

- Early warning systems
- Maintenance
- Modifications of dam operations

It should be noted that monitoring in this context is assumed to include instrumentation, ongoing data collecting from visual observations and measurements, and periodic assessments of structural performance. The non-structural measures will have an influence on the consequences of flood hazards. Some of the measures mentioned here have already been implemented by many dam owner organizations, and, as for Norway, dam safety legislation has included most of them as legal requirements (OED 2001). As the objective of this thesis is to study operation of dams during floods, structural performance monitoring and maintenance is not discussed here. More details on the subject and some references can be found in, for example, ICOLD (2001), Jansen (1980) and ICOLD (1987). An overview and discussion on the subjects of risk assessment and emergency planning are given in Chapters 3 and 4. Aspects of training, early warning systems and modified dam operations are discussed in Chapter 4.

2.7 Possible effects of climate change

Much research has been done over the last decades on climate change. Possible climate change scenarios based on both natural variations, and assumptions about future manmade emissions into the atmosphere of so-called greenhouse gases, have been developed. The Intergovernmental Panel on Climate Change has published a report on the regional impacts of climate change (IPCC 2000). The IPCC report indicates a warmer climate and more precipitation in Northern Europe, the effect of which will be an increase in river runoff leading to increased flood hazard. It is worth noting, though, that IPCC regard these conclusions as being rather uncertain. For Norway, some preliminary results from a project called RegClim (Regclim 2000) suggests a 2° C temperature and a 20 % precipitation increase in the period 2000 - 2050. These results are based on a 100% increase in CO_2-concentration for the same period. At the same time, wind velocities and the number of storms are expected to increase, especially in Mid-Norway. Predictions of climate change effects on floods in Norway were made in the beginning of the 1990s according to Roald (1999). Roald found that none of the predicted effects were recognized in 1999. However, a study of past and future variations in climate and runoff in Norway (Førland et al. 2000) shows that there has been an increase in runoff values during the last decades of the 20th Century in southern and central Norway.

According to Førland et al., the total runoff volume after 100 years could increase by 20% in western Norway. The effects of climate change on flow regimes also proved to be strong.

Changes in temperatures may influence on the probability of jøkulhlaups, as well as on other ice-problems related to floods such as aufeis and ice-jams. A recent jøkulhlaup at Blåmannsisen glacier in northern Norway is believed to be a result of climate changes (Engeset 2001). The jøkulhlaup was probably caused by a deficiency in ice-mass, that is, the accumulation of winter precipitation (as snow) could not compensate for snow and ice melt during summer. However, this theory is not yet verified. The jøkulhlaup at Blåmannsisen resulted in a 2.5 m increase in the water level in the Sisovatn reservoir, corresponding to a 40 million m^3 increase in reservoir volume. The water level in the previously glacier-dammed lake, which released water into Sisovatn, decreased by 70-80 m (Figure 2.9). Due to the low reservoir level prior to the jøkulhlaup, the Sisovatn Dam and downstream areas were not affected (Josefsen 2001). An evaluation of the Blåmannsisen jøkulhlaup, including measurements, has just started. An interesting point in the case of Sisovatn is that a jøkulhlaup from Blåmannsisen had not been considered a probable exceptional load on the Sisovatn Dam, even though jøkulhlaups are particularly mentioned in the previous dam safety regulations (NVE 1986).

Figure 2.9 Emptied lake after jøkulhlaup at Blåmannsisen Glacier (Engeset 2001).

A study from China indicates that there has been a change in magnitude and frequency of floods (including jøkulhlaups) and an extension of the glacier and lake system of the Kunmalik River. Information about jøkulhlaups from a glacier-lake formed by the Merzbacher glacier is available back to 1870, and there are observations of discharge from 1955. After the 1950s it seems as if the peak discharge and frequency of the jøkulhlaups had increased. There has been a general retreat and decreasing thickness of the glaciers over the same period, and this is explained by a general rise in temperatures and a wetter climate (Jingshi and Fukushima 1999). The conclusions from the Merzbacher glacier on the Kunmalik River are similar to the preliminary conclusions from Blåmannsisen glacier in northern Norway.

According to Jingshi and Fukushima (1999) and Engeset (2001) the decrease in glacier thickness and increased frequency or magnitude or both of jøkulhlaups can be used as an indicator of a warmer climate. Studies of long time flood series may also be evidence of climate change. Studies from Sweden, Norway and China, respectively, show very clearly that some periods tend to be richer in floods than others (Guowei and Jingping 1999; Lindstrøm 1999; Roald 1999), which is explained by a natural long-term variation. However, the study from China, including 500 years of observations, concludes that the extreme flood situation may have become more serious over the first half of the 21st century (Guowei and Jingping 1999). Guowei and Jingping assign this to increased human activities and climate change, but whether a coming (or ongoing) climate change has been caused by increased emissions into the atmosphere or are natural variations are not discussed.

2.8 Discussion

Selection of design flood seems to be very much a matter of tradition and there are consequently variations from country to country. There seems to be a trend of selecting design floods with respect to the hazard classification of the dam; few countries use economic risk assessments to determine the optimum design flood. The design floods of high hazard dams are usually the PMF or another very severe flood. The method of estimating the flood is usually chosen according to data availability. Due to the uncertainties inherent in all the available flood estimation methods, ICOLD recommends that whenever possible several methods should be used (ICOLD 1992). A design flood value that is adopted after a reasoned and critical comparison of the results given by several different methods is more justifiable than one from a single method. This principle is practiced in Norway where the inflow design flood normally is calculated both by flood frequency analysis and rainfall/runoff models assuming that precipitation with a return period of 1000 years results in a flood with the same return period (Pettersson 1998). Care must be taken, however, in river basins where melt-floods are dominant.

Some dams have been exposed to floods with the same magnitude as, or even exceeding, the design flood. In some cases, the design flood was found, with hindsight, to be underestimated. Underestimation can be either due to deficiencies in the estimation methods, or changing meteorological or hydrological conditions or both, which were not accounted for. However, floods that are considerably smaller than the estimated design flood may also be hazardous to dams due to various reasons such as:

- Unexpected loads not considered during design (for example waves in combination with high reservoir level)
- Undetected deterioration of dam structure or appurtenant works
- Malfunctioning of spillway
- Operational procedures not followed (human error)

In addition, floods and possible appurtenant loads from lightning, wind and so on have a tendency to trigger several failures in a dam system (common cause failures) such as the disruption of both electricity supply for gate operation and communication lines for data-transfer of gauged water levels. Apart from external loadings, such as floods and extreme weather, common cause failures can also be a result of a system component failure, which will lead to other components failing as the loading increases (Jenssen 1997). Thus, the simpler a dam system is, the better. However, economic and other practical considerations have often resulted in solutions other than those that are optimal from a strictly safety point of view. This is, among others, the reason why there are many complicated spillway gates despite several studies concluding that free overflow crests are most reliable with respect to the passage of floods, especially major floods. The same explanation holds for the choice of dam type, dam site (foundation) and so on. In other words, dams cannot be designed to be 100% safe against floods (or other loadings). It is therefore recommended that redundancies in technical systems should be emphasized (Bister and Delliou 2000; Kjellesvig and Midttømme 2001).

Independent of original design, there is a need to upgrade a dam system over time. Apart from improvement of technical solutions and dam condition, non-structural risk reduction measures will be advantageous to ensuring safe dams. Possible non-structural risk reduction measures include, among others, emergency action plans, warning procedures, operation rules and well-trained staff. Risk assessment is probably the best basis for prioritizing measures (whether structural or non-structural). The use of risk analysis and assessments will be discussed further in Chapter 3. When performing analyses, consideration should be given to local features of the catchment as well as possible flood scenarios and other loading scenarios for the region. Cold regions problems must, for example, be included in Norway, while hazards related to volcanoes can be eliminated. The ongoing research into climate change is also worth noting, and results from this should probably be included in future analyses, at least if the results indicate potentially major changes in flow regimes and runoff volume.

Other possible climate change related consequences, such as increased probability of jøkulhlaups should also be assessed. The jøkulhlaups mentioned above are floods caused by sudden releases of water from glacier-dammed lakes. Similarly, floods can result from upstream dam failure or slides or rock falls into reservoirs, which are not necessarily related to rainstorms or extensive melting (natural floods). Contrary to rainfall or melt generated floods, floods caused by sudden water release or extreme surges in reservoirs will probably appear with little or no warning time. Thus, even where there is only the smallest probability of such floods, measures should be taken to avoid intolerable consequences downstream.

3 RISK ANALYSIS

"The "opponents" to the use of risk analyses should be reminded that: uncertainties do exist. Risk analyses do not create them, but expose them." (Høeg 1997)

3.1 Introduction

Risk analysis has gained acceptance within dam safety management over the past decade, and some countries have changed to risk based management from traditional standards based safety management (Figure 3.1). Several conferences have included risk analysis for dams in this period. The General Report from Question 76 ("The use of risk analyses to support dam safety decisions and management") at the ICOLD congress in Beijing provides a thorough review of much of the available literature (Kreuzer 2000). Some recent views on risk management for dams are given by Bowles and Anderson (2001), as well as by Mason and Scott (2001), who also discuss the report from the World Commission on Dams.

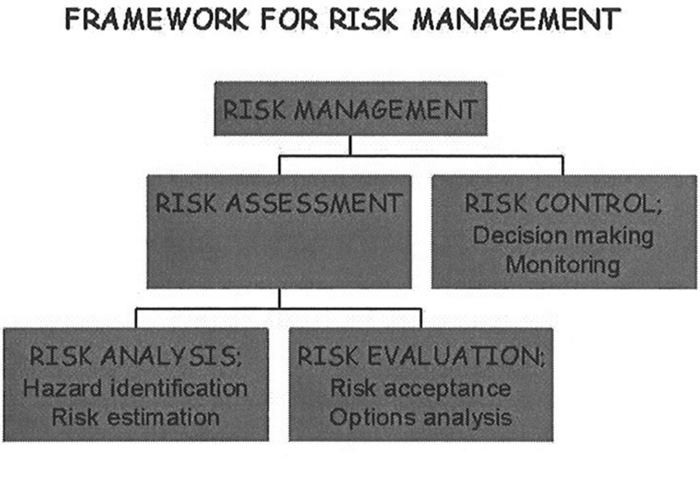


Figure 3.1 One of many ways to display what risk management is all about (from HP&D 1998)

3.2 Why use risk analysis for dams?

Risk can be expressed as the product of probability and the consequence of a given event (incident) or failure mode. Thus, a complete risk analysis must comprise both an evaluation of probabilities for relevant failure modes as well as a consequence analysis. In other words, risk analysis should provide answers to the following questions:

- How can failure occur?
- How likely is it?
- What would the consequences be?

According to Høeg (1998) risk analysis functions as a framework for systematic application of engineering judgment and available statistics in decision-making. One could also add traditional deterministic analysis, which is an important element of many risk analyses. There are several reasons for implementing risk analysis as a tool for dam safety management, whether it be for design of new dams, reassessment of existing dams or comparison of risk imposed by dams with other risks in society (Salmon 1997; Høeg 1998; Åmdal 1998b). For existing dams, the main purpose seems to be decision support both to decide whether safety improvements are required and allow reliable comparisons among alternatives for remedial measures. Risk analysis can provide useful information about vulnerable parts of the dam construction and its surroundings as well as weaknesses in the dam owner's organization. This makes risk analysis applicable for the preparation of emergency plans. Risk analysis can be in the form of a diagnostic analysis improving the understanding of dam behavior (Vick 2000) and can thereby have a didactic value for young inexperienced engineers (Lafitte 1997). Finally, risk analyses may serve as a basis for risk communication with third parties (Åmdal 1998b).

3.3 Present use of risk analysis in dam safety management

Some of the most active countries with respect to application of risk analysis for dams are Canada, Australia, the Netherlands, USA and South Africa (Oosthuizen and Elges 1998; Vick 1997). More are currently establishing risk-based guidelines or are conducting research within this field. According to Kreuzer (2000), the reasons for the growing interest in the use of risk analysis for dams are:

- Increasing age of dams
- The view that risk analysis allows safety margins to be more realistically evaluated than traditional (deterministic) safety criteria
- The public desire to quantify the risk of catastrophic events triggered by the use of risk analysis in the nuclear and aeronautical industries
- Judgment of safety within the context of changing climatic conditions
- Increasing downstream consequences resulting from increasing population density
- Possible economic benefits arising from risk based assessments

Results from a risk analysis can be judged by using decision criteria (risk acceptance criteria) including life safety and economic criteria. Life safety can be expressed by societal and individual tolerable risk criteria. Individual risk is the probability of loss of life (LOL) per person per year. BC Hydro in Canada and ANCOLD have implemented LOL-criteria in dam safety management (McDonald 1997; Hartford 1997). Societal criteria, that is the socially acceptable risk (SAR) or probable loss of life (PLL), are commonly expressed as F-N curves, showing frequency of occurrence versus severity of occurrence. Some proposed F-N curves in dam engineering are shown by Høeg (1996). Kreuzer (2000) points out that some skeptical views on the use of F-N curves have recently emerged in Canada and USA.

3.3.1 Risk analysis methods

Several risk analysis methods have proven to be appropriate for dam safety assessments from the simple preliminary hazard analysis to the more extensive event tree or fault tree analysis. An overview of relevant methods is given in the Norwegian guidelines for application of risk analysis on dam structures (NVE 1997). The described methods are shown in Table 3.1. When looking at the methods already implemented in safety assessments in Norway and other western countries, probabilistic risk analyses (event tree analyses) seem to be preferred by the dam owners along with simple methods such as Failure Modes, Effects (and Criticality) Analyses (FMEA/FMECA) and Preliminary Hazard Analyses (PHA), see for example Åmdal and Odgaard (2000) and Kreuzer (2000). According to Høeg (1996), the main applications of probabilistic risk analyses in dam engineering are:

- Design of new dams
- Selection of alternatives for remedial actions and upgrading
- Comparison of dam related risk to other risks in the society

The simple methods are applicable as a first step in more complex risk analyses Rausand 1991. This has also been recognized within dam safety management, see for example Fell (1997), Hartford and Salmon (1997) and McDonald et al. (2000). In Norway PHA is primarily promoted as a suitable method for preparation of emergency plans for dams (Enfo 1999a; NVE 1997), perhaps in combination with other methods for specific parts of the dam or for specific situations or incidents.

Table 3.1. Risk analysis methods recommended for dam safety analyses (NVE 1997)

ANALYSIS METHOD	ABBREVIATED	PRIMARY RANGE OF APPLICATION
Preliminary Hazard Analysis	PHA	Identify why things go wrong
Failure Modes and Effects Analysis	FMEA	Identify why things go wrong
Failure Modes, Effects and Criticality Analysis	FMECA	Identify why things go wrong
Fault Tree Analysis	FTA	Evaluate cause relations and calculate failure probabilities for composite systems
Event Tree Analysis	ETA	Display a course of events and possible consequences
Safe Job Analysis	SJA	Identify hazards in every job step

FMECA has been used in the United Kingdom for some years and is regarded as a cost-effective complement to existing dam safety approaches (Sandilands and Findlay 2000; Beak et al. 1997). The overall opinion in the UK seems to be that there is no need for the sophisticated probabilistic analyses, the reason probably being the long record of no failures and the perception of having robust dams (conventional structures, good foundations and few gated spillways). In addition, fairly strict requirements on dam safety issues have been present for many years, and dams are regularly assessed to check their compliance with these requirements. Similar opinions, perhaps in addition to a strong belief in monitoring and warning systems as a superior safety measure, may be the reason why other countries, such as Switzerland and France, have also been reluctant to start using risk analyses for dams.

As mentioned above, many countries seem to prefer event tree analyses, particularly for complex systems and in combination with fault tree analyses or reliability block diagrams. Practical use of, and experiences with, ETA are described in Section 3.4 and by for example Bartsch and Gustafsson (2000), Dise and Vick (2000), Funnemark et al. (2000) and Hartford et al. (1997). An example of risk analysis for a spillway gate using FMEA, FTA and ETA is presented by Berntsson (2001), while Åmdal (2001) and Cyganiewicz and Smart (2000) give an overview of risk analysis methodology based on event trees.

3.3.2 Assigning probabilities

The challenge of assigning probabilities to failure modes or events can be met by expert judgment (quantified by subjective probabilities), analytical methods (by introducing parameter uncertainties in the deterministic model for the event considered) or statistical data relevant to the situation (Hartford and Salmon 1997; Høeg 1998). Expert judgment is, in practice, an attempt to quantify judgment based on all the available information. The US Bureau of Reclamation has developed a list of verbal-to-numeric transformations (Table 3.2) to help experts assign a numeric value when estimating probabilities (Cyganiewicz and Smart 2000). The same method has been adopted in some Norwegian cases and is recommended in the Norwegian guidelines for practical application of risk analysis (Åmdal 2001).

Table 3.2 Transformation of expert verbal assessment of probabilities to numerical value (Cyganiewicz and Smart 2000)

VERBAL DESCRIPTOR	PROBABILITY
Virtually certain	0.999
Very likely	0.99
Likely	0.9
Neutral	0.5
Unlikely	0.1
Very unlikely	0.01
Virtually impossible	0.001

Analytical methods are used for assigning probabilities to design floods, seismic loads etc. Statistical data on dam performance from all over the world are available from ICOLD (ICOLD 1984; ICOLD 1995; ICOLD 1999). In the USA there is a database at Stanford University on the performance of dams, which covers most US dams (McCann 1998). Statistics can also be based on surveys of incidents and failures such as the Swedish survey of spillway gates (Berntsson 2001), and the Norwegian surveys of embankment (Skoglund 2001) and concrete dams (Jensen 2001). In the last few years there have been several proposals to establish a European database in line with the US database presented by, for example, Sims (2001) and Høeg (1998). Any use of statistics, however, requires prudence with respect to the relevance of data. Every dam is unique and worldwide statistics will not necessarily apply to the specific dam in question.

3.3.3 Consequence analysis

A complete risk analysis should also comprise a consequence analysis. Consequences are often divided into economic losses (mostly structural damages) and fatalities. Some also include intangible losses (such as loss of business reputation, environmental and social impacts) in the consequence assessment, as is the case for Hydro-Tasmania in Australia (Stojmirovic and Southcott 2001). There have been attempts to assign a monetary value to human lives (Ellingwood et al. 1993), but the issue is very controversial and is seldom brought up as an interesting approach.

Methods focusing on Population at Risk (PAR) and loss of life have been developed in USA, and Brown and Graham (1998) describe the development up to 1988 as well as the method used by USBR at that time. While material damage can be estimated as a function of dam break flood characteristics, fatalities and injuries to people are far more complicated to estimate due to the fact that people have the ability to escape and survive a flood wave under certain conditions. The USBR-method had equations for estimating loss of life as a function of PAR and warning time. Modification of the estimated loss of life was carried out according to judgment of "unusual local conditions" such as limited escape routes. The method was based on a study of 24 historic dam failures and flash floods in the US, but criticism was later made about the statistical procedures used and a new approach was suggested (DeKay and McClelland 1993). The "DeKay and McClelland"-method is based on a new statistical analysis of the same set of data (with some additional cases), resulting in revised equations for loss of life. Inherent in the method is that people more than 3 hours flood wave travel time distant from the dam are not included in the PAR-value. In addition, depth and velocity of floodwater (expressed by a "Force value") are included in the method. The method is not recommended for the estimation of loss of life upstream of areas with very large PAR, when no warning of dam failure is given.

Weaknesses in both the above mentioned methods have been recognized (Graham 1999), first and foremost related to shortages in the basic data. This implied that the equations developed previously, reported by DeKay and McClelland (1993) and Brown and Graham (1988), were probably not applicable for use with dam sizes and types, failure causes, flood severity and warning scenarios not reflected in the data set. Thus, Graham (1999) introduces a new method, which considers flood severity, amount of warning and a measure of whether people understand the flood severity. The method was developed using an enlarged data set. Even though this work seems to represent an important development in terms of loss of life estimations, there are still some unsolved problems related to warning time, as discussed by Stojmirovic and Southcott (2001). Application of the method outside USA may not be relevant either, mainly due to geographical differences. For example in Norway, settlements are scattered with low populations so that evacuation will probably be individual rather than organized. A method has been developed for analysis of consequences adapted to Norwegian conditions (Funnemark et al. 1998). The method introduces a comprehensive investigation of the factors influencing the ability of people to escape. These factors include reliability of warning systems, warning time, evacuation efficiency, the amount and composition of the population at risk and so on. The method is based on an event tree methodology and traditional calculations of dam break floods by standard flood routing models in order to find the dam break flood characteristics.

3.4 Experiences and practice in Norway

An overview of how risk analyses had been used in Norway up to 1997 is given by Torblaa (1997) while the Norwegian Electricity Industry Association (EBL) looked at the specific case of Norwegian dams and appurtenant structures up to 2000 (EBL 2001). The first guidelines referring to risk analyses in Norway were those on safety evaluations for the design and construction of offshore installations issued by the Norwegian Petroleum Directorate in 1981. In 1991 an official Norwegian Standard for risk analysis was issued. Meanwhile two risk analyses for dams in operation had been carried out in a project initiated by NVE and the former Norwegian Water System Management Association (NVE and VR 1987). In the period from 1987 to 1995, there were only a few other attempts to carry out risk analyses for dams, spillway gates and penstocks. Among these were risk analyses for seven dams in order to evaluate the probability of dam failure due to overtopping. Around 1995 a general interest in risk analyses evolved among dam owners as well as with NVE, but contrary to the offshore industry the focus was on analysis of structures in operation. Some dam owners joined forces to start a project on estimation and comparison of the probability of failure in large rockfill dams using event trees (Johansen et al. 1997). Some of the conclusions were:

- Risk analysis is an important diagnostic tool in identifying alternative ways of reducing failure probabilities
- Risk analysis helps quantifying the degree to which several important safety features contribute to reliability

After 1995 several comprehensive risk analyses, mostly probabilistic event tree analyses, were performed for Norwegian dams, for examples the concrete buttress dam Svartavatnet (Åmdal 1998a) and the rockfill dam Valldalen (Funnemark et al. 2000). The methodology used has often been to construct event trees on the basis of dam site inspection and initial screening of failure modes. Failure sequences are developed and decomposed into component events. Probabilities of the component events are mostly determined by engineering judgment based on statistical and subjective, degree-of-belief probability interpretations. The overall failure probability is calculated from the component event probabilities. The event trees are thereafter examined to determine why certain failure modes give larger contributions than others, and possible reasons are carefully examined and reviewed. An overview of the probabilistic risk analysis methodology used for Valldalen Dam is shown in Table 3.3. The dam owners have recognized these probabilistic risk analyses as a means for quantifying the reliability of their dams and for identifying potential dam safety improvements.

Several working groups with representatives from NVE, dam owners and consultants were engaged in the revision of the Norwegian dam safety regulations (see Section 1.1.3). The recommendations, with respect to risk analysis, from the working group on emergency planning and risk analyses was summarized in the NVE guidelines for application of risk analyses for dams issued in 1997 (NVE 1997; Åmdal 1998b). The guidelines are informative and focus on when or whether risk analyses are relevant. However, they are not very detailed when it comes to practical implementation of the various risk analysis methods. Thus, EBL has recently developed additional guidelines describing quantitative methods (mainly event tree and fault tree methods) in more detail (Åmdal 2001; EBL 2001). The project report on preliminary hazard analysis for emergency planning can also be used as practical guidelines (Enfo 1999a). Other countries that have developed practical guidelines on the use of risk analyses are for example Canada (Hartford 1997) and USA (USBR 1999). In the revised Norwegian dam safety regulations there is one section covering risk analysis; *§2-8: The Norwegian Water Resources and Energy Directorate may demand risk analyses conducted by the responsible dam owner.*

Table 3.3 Probabilistic risk analysis methodology (Funnemark et al. 2000)

STEP	ACTIVITY	COMMENT
1	Site inspection	Dam and dam site inspection to familiarize with the structure and site conditions.
2	Hazard identification	Identify all potential failure modes. Screen out hazards not relevant for the dam.
3	Construction of event trees	Consider only the events leading to dam failure; input from step 2. Develop detailed failure sequences.
4	Probability assessment	Assign probabilities to the events in the event trees based on statistics and engineering judgment.
5	Evaluation of results	Calculate the total probability of dam failure. Examine the event trees to range failure modes or sequences with respect to their contribution to the total probability.

3.5 Discussion

Safety criteria for dams tend to change with developments in research and experience gained from dams in operation. Risks imposed by old dams should not be any higher than risks imposed by new dams constructed according to the newest criteria (Høeg 1998). Thus, the safety of existing dams must be reviewed once in a while. A common approach to reassessment of existing dams is to check whether the dam can meet hydrological and structural safety criteria based on engineering practice, guidelines or regulations. Bowles et al. (1997) define this as standards-based approach and discuss whether this approach is incompatible with a risk-based approach. A risk-based approach is defined in this context as *"the approach to design and evaluation of dams in which an acceptable safety condition is defined by use of information provided from a risk assessment and other decision inputs"*. The main conclusion given is that risk assessment is a necessity while standards-based solutions may be justified in some cases of dam rehabilitation. One of the objections to the standards-based approach is the fact that it tends to focus on worst case scenarios and thereby pays too little attention to deficiencies associated with lower magnitude, more frequently occurring loading conditions, which would have been highlighted in a well-performed risk analysis. According to Salmon (1997) this has in fact also been put forward as a criticism of risk analyses, but he regards it as a criticism of engineering in general.

It is worth noting, that the use of risk analyses includes the same types of investigation and deterministic analyses as for traditional safety evaluations, but using risk analyses can help when focusing on the most important questions early in the study. Based on long-term experience from the offshore sector in Norway, Kortner (1997) concludes that technical standards, codes and good engineering practice should be used as long as it is justifiable. As a consequence, risk analysis should be left for the "large uncertainty" problems and be regarded primarily as a tool for decision support. This is probably not inconsistent with Bowles' view, but is a statement intended particularly for comprehensive probabilistic analyses, which has been the practice in the Norwegian offshore sector.

Taking into account potential loss of life and economic losses from a failure, it may be worth including expensive and time-consuming probabilistic risk analyses in the ongoing safety management for large dams. Lempérière (1999) supports this view in his examination of what sort of analysis is appropriate for various dams. He also recommends risk analyses for medium and small dams to be organized by the regulatory authorities, and that many dams are analyzed by a single team focusing on a few main risks in order to save time and money. According to Lempérière this has proven to be successful in France. Furthermore, he recommends increasing attention given to the significance of human behavior on the total risk. Study of human behavior has so far not been applied to dams in the scale it may deserve. Human behavior may influence both probability and consequence of failure. The probability may be influenced by, for example, decisions on whether to operate a spillway gate (or not), and the consequence by, for example, human response to warnings of dam failure. Studies on risk perception (which is of importance for human response) have been carried out recently among people living in areas downstream of dams (Maijala et al. 2001; Almeida 2001). In the case of human behavior it is important to consider cultural differences between countries and maybe also within countries. In other words, further studies on human behavior (human error, risk response and so on) should be carried out.

Discussions on "risk acceptance criteria" tend to be emotional partly because implementation of such criteria, directly or indirectly, means that a monetary value is put on human lives. This is ethically not acceptable in many cultures. A way of avoiding this resistance is to be cautious with language, for example, the term "public protection guidelines" should be used instead of "acceptable risk criteria", and "cost of saving one more life" instead of discussing the "monetary value of a life lost" as suggested by Høeg (1997; 1998). The US Bureau of Reclamation has already accomplished this (USBR 2000). Some suggestions on how to avoid the problem of putting a monetary value on human lives, when selecting alternatives for upgrading the safety of a dam, are given by Bowles et al. (1997). The recommendation is to evaluate cost effectiveness for non-structural and structural alternatives by calculating a cost per life saved, and compare the cost for each alternative with similar costs for other facilities.

A complete and thorough screening of all possible loads and load combinations, and all possible combinations of interactions, is necessary for a risk analysis to be defensible. A qualitative FMEA (Failure Modes and Effects Analysis) appears to be the minimum level that can reasonably be considered to be credible and defensible (Hartford and Salmon 1997). There should also be certain requirements with respect to the analysts, as well as to the analyses. Another way of ensuring credibility is by putting effort into the documentation to make the logic structures and probabilities traceable to their respective source. One of the major challenges is to find better analysis methods for estimating probabilities and to make expert judgments "as objective as possible". Salmon (1997) addresses the need for better analytic methods to estimate the probability of various loadings. The need for better insight into dam failure mechanisms is also recognized, for example for traditional Norwegian rockfill dams (see Section 2.4.3).

A paper from the Department of Natural Resources and Environment in Victoria, Australia, states that a dam safety regulation framework should promote risk management and not hinder it, and be the platform for the development of a risk analysis framework (Watson and Perera 2000). With the present regulations and guidelines issued by the Norwegian authorities, Norway seems to be moving slowly in this direction. NVE has already accepted risk analysis as a tool for safety reassessment and has recognized how risk analysis can give us insight into dam performance. Preliminary hazard analysis has been emphasized the most by NVE, as a tool for performing emergency analyses and as a first step towards extensive risk analyses. There is a reluctance in NVE for adopting the use of risk acceptance criteria, which to date has been introduced by only one Norwegian dam owner (Molkersrød and Konow 2001).

ICOLD emphasizes the need for taking operational considerations into account when hydrological safety of dams is evaluated, because the extreme meteorological events causing severe floods also produce emergency situations for the dam operators (ICOLD 1992). The event tree method is probably the best method in use for analysis of operational aspects. Common for the risk analysis methods used in dam safety assessments, including the event trees, are that they focus on single dams. During floods in river basins with more than one dam, this approach may not be sufficient, as is discussed further in the following chapters of this thesis. There is a need to focus on the safety of each dam separately as well as focusing on the safety of a system of dams during a flood.

By leaving the controversial issue of risk acceptance criteria, and focusing rather on the diagnostic risk analysis, as described by Vick (2000), risk analysis can be a valuable tool in dam safety management, particularly for reassessment of existing dams and for preparation of emergency plans. However, the risk analysis methodology must be adjusted to the problem addressed and to the complexity of the dam to make the process cost effective. It is believed that the best approach is to use simple methods whenever adequate and reserve the extensive probabilistic risk analyses to complex problems and complex dams. Risk analyses evidently increase our knowledge of dam behavior. Still, there are several issues that have to be resolved, such as the problem of assigning probabilities. Future research in, for example, methods for flood frequency analysis and mechanisms involved in failure of dams should be emphasized. In order to be able to analyze handling of floods in river systems, methods focusing on systems of interdependent dams should be developed. The significance of human behavior to dam safety also deserves increased attention.

4 EMERGENCY PLANNING AND TRAINING

4.1 Introduction

Absolute safety against adverse incidents and failures can never be guaranteed in any part of society. Thus, even owners of dams designed and constructed according to existing laws and regulations should have emergency action plans in order to reduce consequences of such incidents and failures. Emergency action plans should be prepared for both the construction phase and the first filling of the reservoir as well as for the operational phase and for prospective decommissioning. This chapter addresses the characteristics of emergency action planning, with emphasis on dams in operation, and gives an overview of recent developments and possible improvements. Most attention is paid to the ability to the dam owner to manage extreme and unexpected incidents (safety of the dam structure) in order to avoid, or at least reduce, the consequences downstream. Although of importance, warning procedures and evacuation of third parties (downstream safety) are outside the scope of this thesis and are not covered in as much detail.

Terms used in emergency management for dams differ in different parts of the world. Even within the ICOLD bulletin on Dam Safety Guidelines (ICOLD 1987), there is a lack of consistency as the terms emergency action plan and emergency operation plan are seemingly used with the same meaning. Others use the terms emergency plan, emergency preparedness plan, disaster preparedness plan and contingency plan, but the term emergency action plan (EAP) seems to be the most preferred. Cavanaugh (1989) defines an emergency action plan as:

> *A formal plan that identifies potential emergency conditions at a dam and prescribes the procedures to be followed to minimize property damage and loss of life.*

Accordig to Schuelke (2000), the emergency action plan identifies "who will do what" in an emergency. The plan contains preparedness information, including (but not limited to) the types of emergencies, how to detect them, who to notify, where to find repair materials that may be needed in an emergency, and inundation maps reflecting dam failure and sometimes other major floods. For simplicity the term emergency plan is used in much of this thesis, especially when speaking in general terms, as are emergency action plan (EAP) and coherent emergency action planning.

4.2 Planning models

According to Dynes (1989) there seems to be a dominant planning model used in emergency planning. This model is labeled the "military model" to indicate its origin. Dynes gives an overview of its background with examples from USA. The first comprehensive US legislation to deal with emergency planning was the Federal Civil Defense Act of 1950. The primary objective was to provide a system for civil defense of life and property against enemy attack. With time, the focus changed to local emergencies, but the military model remained almost the same. Thus, the military model assumes that an emergency will be sudden and have a drastically different social situation than normal. The fact that some emergencies develop slowly is handled by defining terms for stages, such as "alert", "in-plant emergency", and "community emergency". In short, the main principles of the military model are that emergencies are characterized by chaos, which can only be eliminated by command and control. Thus, organizations that hope to be effective in an emergency need to change their structure towards a military structure. Emergency plans based on this model tend to be unfamiliar when implemented in civil society because the plans refer to an unfamiliar organization structure.

Dynes suggests a more suitable model of emergency planning based on problem solving where the keywords chaos, command and control are exchanged with continuity, coordination and cooperation. The problem-solving model assumes that emergencies in most cases develop over time and social systems and structures (such as organizations and communities) will be relatively intact, regardless of how extensive the emergency is. Thus, it is not necessary to change the pre-emergency organization drastically in order to handle an emergency. An emergency will in most cases involve various organizations and planning should be directed towards inter-organizational coordination (and cooperation). Coordination can be improved through common planning and exercises, establishment of personal contacts and so on. By building on the pattern of pre-emergency behavior, detailed descriptions of appropriate behavior for all hypothetical scenarios are not necessary. Planning should be directed towards developing an effective response and improvisation should be encouraged since there is usually more than one way to solve a problem.

4.3 Guidelines for emergency action planning for dams

One of the ICOLD technical committees, the Committee on Dam Safety, has issued guidelines for dam safety including general recommendations for emergency action planning (ICOLD 1987). The guidelines recommend coordination of emergency action plans in river basins with more than one operating system (operating company) and suggest that the plans should be reviewed and updated at regular intervals. Furthermore, the guidelines should give practical recommendations on the contents of emergency action plans including, for example, coordination of emergency relief actions with third parties (such as civil defense, police, hospitals and NGOs). The guidelines also focus on the need for giving the operator's top-level technical personnel the authority to order emergency preventive or repair measures without asking for special authorization from the management. Likewise, clear and easily understandable emergency instructions and procedures should be issued to all operating units, and local operating staff must be provided with instructions to be followed in the event of loss of communication with the central control unit. Finally, the guidelines also recommend training and retraining operating staff to prepare them for emergency situations. The recommendations given by ICOLD seem to follow, for the most part, the principles of the problem-solving model suggested by Dynes. However, in practice components from both models can be recognized. The main issue is, of course, to use principles that are suited to the actual emergency. Emergency procedures developed for the majority of natural hazards will in most cases be different from emergency procedures for war or terrorist attacks.

The ICOLD guidelines are meant to be general to be applicable for most ICOLD member countries. Some countries may, however, find it appropriate to use several elements from the traditional military model described by Dynes due to, for example, their political situation or level of development. Some countries have issued their own guidelines, which more or less follow the ICOLD guidelines; examples from Norway and USA are given below. Descriptions of guidelines and practice from other countries, such as France and Spain, can be found in for example LeDelliou (2001) and Penas et al. (2001). An example from Africa has also been found. The example describes challenges in emergency action planning for the international Zambesi River (Mazvidza et al. 1996). However, neither a worldwide nor a European overview on the status of the legal framework, guidelines or practical emergency action planning for dams has been found. A recently started ICOLD European Working Group on Safety of Existing Dams has planned to survey various safety aspects including emergency action planning among countries represented in the group (Yagüe 2001). The survey will cover criteria and contents of emergency action plans, as well as coordination with authorities responsible for civil defense.

4.3.1 Guidelines in Norway

Prior to the dam safety regulations of 1981, the hydropower sector had been working with emergency preparedness in various forms related to acts of war and sabotage. A department focusing on protection of the national power system (abbreviated KSFN), and a legal framework aimed at securing hydropower facilities were set up in 1948. Military personnel dominated KSFN and their work was classified. They had their own system of classifying dams and other hydropower facilities, and they carried out dam break hazard analyses. The dam safety regulations issued in 1981, stated that all dam owners (not only hydropower companies) must have a plan for coping with extraordinary situations at their dams. In practice, the dam owners met this demand by developing plans for site inspections during severe floods, storms or other unusual events. KSFN was closed around 1990 and its responsibilities taken over by NVE. The requirements for emergency action planning for hydropower dams were augmented in Chapter 6 of the Energy Act of 1990 with the addition of appurtenant regulations issued in 1991.

When the new dam safety management framework was introduced in 1992 (based on the internal control principle), NVE recognized the need for preparing emergency action plans for all dams - as defined according to the dam safety regulations (i.e. not restricted to hydropower dams). There was also a need for more focus on emergencies created by natural accidents than what was provided by the regulations founded in the Energy Act. A letter was sent to all the owners of these dams in May 1993 stating that emergency action plans were required. NVE followed up by issuing guidelines on emergency action planning for dams in 1994 (NVE 1994), as a supplement to the Energy Act regulations. The supplement guidelines were presented to the ICOLD society at the ICOLD Congress in Florence in 1997 (Svendsen et al. 1997).

The guidelines are based on the principles developed by KSFN, and cover the analysis of preceding incidents (events) and the structure of the EAP. The analysis (the emergency analysis) must cover both natural conditions (such as storms, floods and landslides) and malfunction of the system (mechanical failure, transmission- or control failure and administrative failure). A system in this context is regarded as a single dam or several interdependent dams with appurtenant structures. Critical water levels, critical seepage and other critical limits must also be analyzed. The actual EAP is meant to be an operational plan, which focuses on the actions to be taken and the person or group responsible for carrying out those during an emergency. The dam owner is obligated to establish and update the EAP. The guidelines recommend the following structure of the EAP:

1. The initial phase
2. Table of contents
3. Organization
4. Notification plan (who should be notified, in which order, by whom)
5. Action plans (emergency procedures specified for each dam and type of event)
6. Resources (list of internal and external resources)
7. Information
8. Communications
9. Exercises
10. Appendices

The underlying material/documents produced during the planning process can in some cases be large in terms of documents and pages. In order to make the EAP into an easily understood and practical document for use in critical situations, most of this material should be kept in separate volumes.

In river basins with more than one dam owner, the different emergency action plans should be co-ordinated. It is also necessary to plan for cooperation with third parties such as local rescue teams and civil defense. Cooperation with the authorities will become more important with event severity. The regional commissioner (Fylkesmannen) has the overall responsibility for cooperation between civil and military emergency planning and actions. In case of extensive emergencies, the regional commissioner may also take over responsibility for coordination of emergency actions (DSB 2001), for example by establishing KBO (Kraftforsyningens Beredskapsorganisasjon). KBO is an organization responsible for power supply during war and extensive peacetime emergencies according to the Energy Act, Chapter 6.

The Norwegian guidelines on emergency planning for dams recommend preparatory meetings with all relevant organizations, as well as exercises together to become as well prepared as possible. The guidelines also stress the importance of regular revisions and updating of the EAP. Updating of EAPs must be done regularly or when necessary to account for any changes in the system, the surroundings or the organization. New knowledge, new technology, experiences from recent emergencies or experiences from emergency exercises may also result in EAP revision. In other words, emergency action plans and procedures should not be static, but rather be subject to constant evolution and improvement.

The owners of classified dams in Norway differ substantially with respect to resources and competence since the they include "organizations" ranging from single private citizens (small dam owners) to major hydropower or industrial companies (large dam owners). The guidelines are probably best suited to the larger companies as they possess the relevant competence for dam safety. Implementation of emergency action plans in Norway, particularly by small dam owner organizations, has proven to be a challenge, which is referred to further in Section 4.7.

4.3.2 Guidelines in USA

In USA various federal agencies, such as the Bureau of Reclamation (USBR) and The United States Army Corps of Engineers (USACE), have joined forces. In 1989 they issued practical guidelines for developing and implementing emergency action plans for dams (Cavanaugh 1989). These guidelines suggest the following structure for an emergency action plan:

1. Introductory section
2. Responsibilities
3. Emergency procedures
4. Preventive actions
5. Inundation maps
6. Appendices

The structure is in many ways very similar to the structure suggested by the Norwegian guidelines and fits well within the recommendations given by ICOLD. Although terms and the level of detail differ to some extent, the content and the principles are similar. For instance, both the Norwegian and US guidelines emphasize coordination with local officials during planning and exercises.

USBR, in addition to being a federal agency, is a major dam owner in the USA as well as a consultant for other dam owners. Recently USBR realized the need to involve downstream emergency response and recovery agencies. In practice, this means involving them in joint planning meetings, training courses and emergency exercises (Sorensen 1996). Furthermore, USBR has made some progress in the development of methods for emergency action planning for dams (Schuelke et al. 2000). The fact that many dam owners, especially the smaller and non-professional dam owners, have problems getting started with emergency action planning, can be met by offering a template for an emergency action plan. USBR has developed such a template over the last years. USBR has also provided some practical recommendations for emergency exercises, such as a stepwise plan for exercises (i.e., following the principle that "you must learn to crawl before you can learn to walk!") and a form for the evaluation of conducted exercises.

4.4 Emergency analyses

During analyses for emergency action planning, emphasis is put on identifying situations or events, which will initiate the preventive actions to be taken. Hazard identification should be followed by an event analysis. The event analysis should focus on the actual conditions at the site, possible development of damage, availability of resources and other factors governing the ability to cope with the undesired event. The Norwegian regulations state that every structure (dam, pipeline and so on) must be analyzed. Critical limits for the structures should be evaluated and documented as part of the analysis. Based on the analysis, remedial measures should be considered. In cases where physical upgrading is not cost-effective, emergency procedures should be developed. Improbable or inconceivable events should not be rejected during the analysis. According to Langrud (2001), hazard identification may in fact be founded on a slightly paranoid way of thinking, that is, it may be worthwhile to go beyond simple checklists or recommendations given in guidelines.

A discussion and overview of risk analysis methods for emergency action planning is given in (Jenssen 1997). Checklists can be used for hazard identification as a first step in an analysis. Checklists are promoted as a useful method for less experienced people, provided the checklists are prepared by experienced engineers and dam safety experts. The NVE guidelines on emergency action planning provide a checklist of some basic events that must be considered. The preliminary hazard analysis is an alternative method for hazard identification, but it can also be used for evaluations of causes and consequences. An event-tree analysis may be a suitable method for assessment of expected chain of events leading to an emergency situation. Jenssen underlines the need to focus on common cause failures occurring during large floods and extreme weather. He also emphasizes the strength of simple methods. The present trend in risk analysis for dam safety in Europe seems to be to use FMECA/FMEA (Fry 2001). It is believed that FMEA (the qualitative version) can be useful early in the emergency action planning process, and later be extended to an FMECA, in order to introduce a ranking of the undesired events.

4.5 Analyses and systems for flood warning

A study of the potential consequences of dam failure is required in many countries including Norway. Norwegian guidelines for dam break analyses were first issued in 1997 and revised in 1999. Molkersrød and Konow (2001) give a brief description of legal requirements and the guidelines for dam break analysis. The basic criterion is that dam break flood calculations should be performed for all dams in the high and medium consequence classes. Further, calculations must be done for two initial conditions in the river system:

- Q_{1000} (design flood)
- Q_m (mean annual flood)

Skoglund et al. (2001), and Ruud and Midttømme (1998), give a more thorough description of the development of the Norwegian dam break analysis guidelines, including a detailed overview of specific requirements. Dam break analyses are performed in many countries around the world and have also been subject to research and discussions in various forums recently. The topic will not be discussed any further here, but reference can be made to ICOLD bulletin no. 111 "Dam break flood analysis – Review and recommendations" (ICOLD 1998a), which deals with this topic in depth.

The presence of inundation maps resulting from dam break analyses will be valuable for planning downstream evacuation in case of a dam failure. Inundation maps are, in other words, a means for reduction of consequences. Warning systems and procedures will also be of great importance. Some of the flood related dam failures reported in ICOLD Bulletin 99 (ICOLD 1995) would probably have had a substantially smaller number of fatalities if the downstream population had been warned more effectively. In Norway, dam failure warning systems were established during the Second World War in nine river basins (Martinsen 1995). The system adopted was entirely manual and was abandoned after the war. Today an electronic warning system with radio link and sirens has been installed by two dam owners, but NVE has the authority to require warning systems to be put in place at other dams if found appropriate (OED 2001). Warning systems other than those for dam failure may also be very useful for flood consequence mitigation, whether natural or due to a dam break.

The early warning systems may be regarded as measures for reduction of consequences along with evacuation plans and dam failure warning systems. Early warning systems are mostly systems capable of predicting natural floods on basis of observed data and weather forecasts, even though monitoring of dams also can be regarded as early warning systems. A continuous and nationwide flood forecasting system for Norway was established in 1989 (NVE 1999). This system is mostly directed towards municipal administrations as well as the public. Even though the system basically provides qualitative forecasts for large areas, some dam owners may also find these forecasts useful. However, most major dam owners either have some kind of tailor-made system for their own river basins, or rely on a system operated by a basin-wide water management association.

The owner-specific systems require extensive data acquisition and flood simulations by hydrological and hydraulic models representing specific rivers or river basins. These systems may be used for both long-term flood predictions and real-time forecasting and are detailed with respect to estimated flood hydrographs. The increased interest in these advanced forecasting and warning systems is probably a result of the increased focus on energy prices, enhanced by the Energy Act. In other words, the main reason for investing in such systems seems to be production planning; flood-prediction is an added bonus. Simpler systems based on reservoir volume curves and monitoring of reservoir water level or inflow measurements or both from major rivers are obsolete in a world governed by energy market prices. However, these systems may be very valuable during floods, particularly as a backup if communication lines for transmission of data are disrupted (to be discussed in Section 5.13).

Having systems for flood prediction and warning does not guarantee successful downstream risk reduction. The recipients, whether for a severe natural flood or dam failure, must understand the warnings and be able to assess the consequences that can be expected (see Section 3.5).

4.6 Emergency exercises

Emergencies may develop slowly (e.g., long lasting floods in large areas) or abruptly (e.g., earthquakes). The preparedness and response to each emergency will naturally be different. In any case there are two factors that will improve the ability to make the right decisions:

- Knowledge about the dams and their operation (including practical experience gained during normal operation)
- Experience from previous emergencies

The first is merely a question of an individual's job experience within the dam organization and access to adequate and appropriate documentation. Personal experience of emergencies, however, may be very difficult to gain due to their (usually) rare occurrence. One way of preparing for emergencies is to learn about emergency situations through case histories and training courses. The process of developing an emergency action plan is also educational, but the best way is probably to participate in emergency exercises. Even though the format of the exercises and the competence of their participants may differ, they tend to engage people and thereby serve as efficient teaching aids.

4.6.1 Exercises in the USA

The US Federal Emergency Management Agency (FEMA) has prepared a standard terminology relating to emergency exercises (Tjoumas et al. 1996), which is used by, among others, USBR and the Federal Energy Regulatory Commission (FERC). There is a hierarchy of emergency exercises as performed by USBR and FERC (Schuelke 2000; Tjoumas et al. 1996); from the simplest to the most complex they are:

- *Orientation seminar* – meeting between participants, which have a role or interest in an EAP, to discuss the EAP and plans for future exercises
- *Drill* – testing of a single emergency response procedure for example testing validity of telephone numbers
- *Tabletop exercise* – participants meet and discuss a defined event in order to evaluate the EAP and response procedures and to resolve concerns regarding coordination and responsibilities
- *Functional exercise* – actual simulation of dam failure and other specified events where participants from different organizations (State, licensee or local emergency management) are seated around separate tables to simulate their office/emergency operation center. The exercise is performed as role-play with a stressful environment and time constraints
- *Full scale exercise* – the participants play out their roles in a dynamic environment with the highest degree of realism possible for the simulated event

The functional and full-scale exercises are regarded as comprehensive. Comprehensive exercises also involve the active interaction and participation of the licensee with State and local emergency management personnel. Comprehensive exercises are requested about once every five years. According to Tjoumas et al. (1996), one of the primary objectives of a comprehensive exercise is to provide the training and practice required to help each individual to clearly understand the EAP and how to apply it to his own responsibilities. One of two predefined failure scenarios is normally chosen for the comprehensive exercise: a fair-weather failure or a failure during a flood condition. The first is normally preferred due to the element of surprise inherent in a fair-weather failure.

4.6.2 Exercises in Norway

In Norway, emergency exercises have been required since 1994. Along with the development of emergency planning guidelines for dams issued in 1994, NVE and EnFo (now EBL-Kompetanse) have included a practical emergency exercise as part of their joint courses Dam Safety III and Emergency Handling. The emergency exercise included in these courses is based on "role-play" exercises developed within the Emergency Preparedness Section at NVE in the beginning of the 1990s. This kind of exercise is probably comparable to functional exercises as described above. NVE has given requirements on the length of intervals between exercises and have accepted that some exercises can be performed as a drill. The Norwegian emergency planning guidelines for dams (NVE 1994) does not give any specific recommendations on the use of scenarios, but some kind of undesired event is naturally essential in the exercise scenario (see Section 6.2.2). An emergency exercise should be based on:

- The emergency plan (that is the preceding analysis)
- Previous accidents revealing the need for training and exercises
- Previous exercises

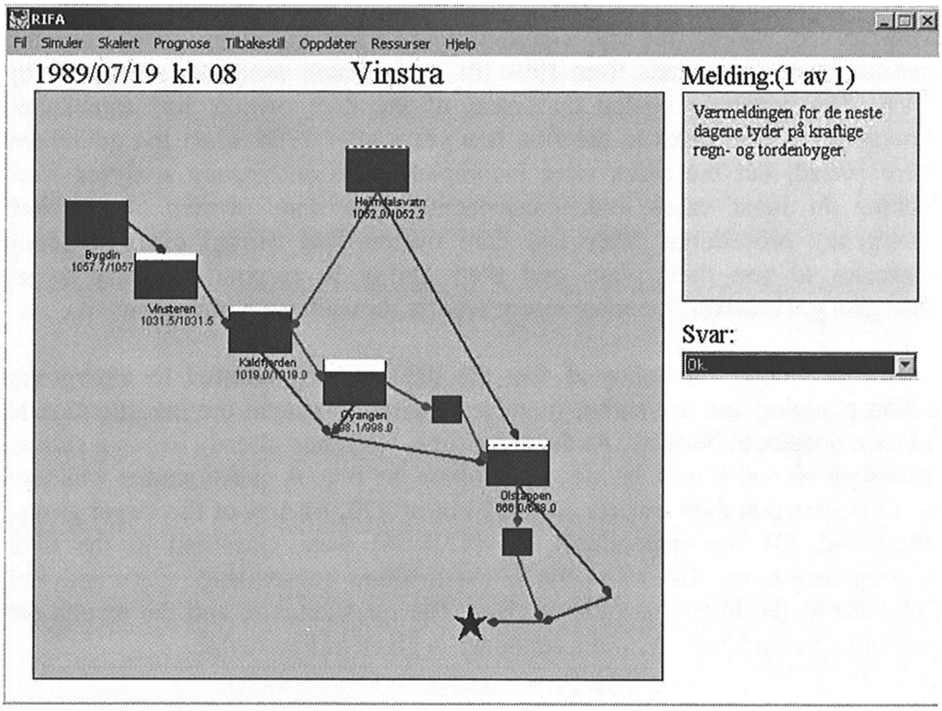
In addition, the guidelines also emphasize that "every employee who has duties during emergencies must participate in exercises".

Several Norwegian power plant and dam owners have carried out functional emergency exercises already, they include GLB and Statkraft. The author has participated in the planning or practical performance (or both) of four functional exercises. Three of these exercises were the first to be performed by the actual dam owner. The most comprehensive, called "Glomvin", was performed in autumn 1994 with participants from GLB (the dam owner and coordinating water management association), Vinstra Kraftselskap (power producer and member of GLB) and NVE (the authorities). The joint emergency exercise was based on a “major flood”-scenario and included non-flood related events such as “personnel missing in the mountains” and “fire in power station”. The author was part in the organizing committee (simulation staff), which sent telephone messages to GLB, Vinstra Kraftselskap and NVE. Many different messages were conveyed including inquiries from worried relatives of the missing personnel and nuisance-calls from stakeholders. The participants were seated in their respective head offices in Oslo and Vinstra and had telephone contact with the simulation staff located in Oslo.

In addition to telephone messages from the simulation staff, the participants were subjected to constant news media inquiries. Several teams of radio and TV reporters, acting as national and local media, visited the personnel at Vinstra Kraftselskap, GLB and NVE in order to reveal any weak points related to admission control in the buildings and release of information to the public. The exercise was scripted, but the simulation staff had to deviate from the script from time to time to respond properly to reports and inquiries from the participants. Immediately after the exercise, the participants were assembled and debriefed, and a report was made in order to provide input for revising the EAPs of the different organizations. The exercise was expensive for the parties involved, however the lessons learnt proved to be very valuable less than a year later in 1995, when a flood hit southeastern Norway (see Section 5.9).

Comprehensive emergency exercises require much preparation and resources, making them expensive and time-consuming. Several dam owners have expressed an interest in investigating cheaper alternatives. Consequently, EBL decided to develop a new computer based training simulator for accidents in rivers, and the River Flood and Accident Simulator (RIFA) is now available (Alfredsen et al. 2001). The simulator is well suited for introductory training of new personnel as well as regular refreshing and upgrading, but it is not meant to replace functional exercises. By using (or playing) RIFA, dam personnel will gain a better understanding of the river system: how it reacts to large floods, and how the flood can be controlled by the operation of reservoirs and hydropower plants. A variety of external disturbances and adverse situations, such as media pressure, inundation of roads and property, gate failures, are also simulated. RIFA can be set up with time-dependent changes in the operation of reservoirs. Changes in operation pattern can also be linked to specified limits, such as critical water levels or discharges, being exceeded. In other words, iterations of flood routing throughout the river system, necessary due to time-dependent or level-dependent changes in operation of any of the reservoirs, are handled automatically by RIFA. Error in prognosis can also be part of a RIFA setup.

RIFA includes a graphical user interface system, a game engine, a river system model and a hydrological and hydraulic simulation system (Alfredsen 2001; Alfredsen and Midttømme 2001). RIFA relies on the input of a flood event (hydrologic and hydraulic data) and a detailed script for the game engine. In addition to the messages to the player, given as text-messages on the screen, the scripts for RIFA include alternative responses to each message. The choice of response may have an influence on the user's ability to operate the system, either by triggering new messages or by occupying resources. During a RIFA simulation, the player is able to operate gates, run prognosis after changes in release and send messages. Gate operations and malfunctions of gates or turbines are visible on the screen as the simulation proceeds. RIFA can be adjusted to a specific river system or it can be used with a default river system. If adjustment to a specific river system is wanted in order to provide dam operators with realistic training, the system specifications must be changed for local conditions, as must be the flood scenario.



Værmeldingen for de neste dagene tyder på kraftige regn- og tordenbyger.

Figure 4.1 Typical screen picture in RIFA with message and response

4.7 Emergency action planning for dams in Norway

Emergency action planning for dams is a rather new requirement in Norway (see Section 4.3.1). In order to help dam owners get started, NVE and EBL-Kompetanse arranged a seminar for emergency action planning in 1995 (Grøttå et al. 1995). The seminar included practical examples of emergency action plans for small and large dam owners respectively. Another seminar was offered in 1999 by NVE with special emphasis on emergencies caused by dam failure and extreme floods (NVE 1999). This seminar covered not only the role of dam owners, but also the role of the local community, civil defense and others involved. At that time, despite the efforts made by NVE and EBL, it was believed that many Norwegian dam owners had not fulfilled their requirements for emergency action planning. It was therefore decided as part of this doctoral program that the status of emergency action planning for Norwegian dams had to be studied.

Hence, a preliminary investigation of emergency action planning for dams in Mid-Norway was carried out. The investigation was based on reports covering internal control revisions from 1994 till 2000, which were made available by NVE. The reports revealed that most of the dam owners had established emergency action plans in the first few years after 1994 when the guidelines were issued, but the plans were incomplete. The emergency analyses were lacking in most cases and, consequently, the dam owners also lacked emergency procedures. Very few dam owners had carried out emergency exercises to test their plans and their ability to respond properly to an emergency. However, the most recent reports showed some improvements.

This first evaluation indicated that the dam owners resisted to emergency action planning and the author therefore wanted to extend the investigation to all dam owners in Norway. At the same time, NVE had already begun a similar investigation and it was decided to combine the two. A questionnaire was sent to all Norwegian dam owners and 228 out of 270, 84.4 % of the target group, responded. Of the respondents, 47 (17.4 %) were classified in the high consequence class, 109 (40.4 %) in the medium consequence class and 114 (42.2 %) in the low consequence class. The questionnaire and the results are presented in Appendix A, and a summary is given in Figure 4.2.

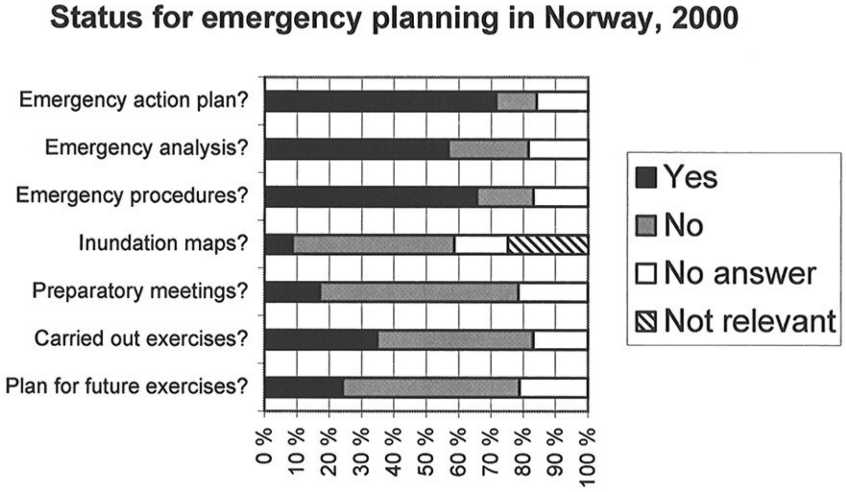


Figure 4.2 Response to inquiry on emergency action planning

It should be noted that some of the replies were not complete. Consequently the number of "no answer" may vary from question to question. The 42 non-respondents are also included in the results. An interesting point is that some dam owners would not accept that the requirements applied to them. Some dam owners in the medium consequence class refused to accept the requirement on inundation maps, while others in the low consequence class did not accept that they had to prepare emergency action plans. It should be noted that inundation maps are not required for dams in the lowest consequence class. The answer "not relevant" to the question about inundation maps therefore applies to all low consequence class dam owners.

The relative number of dam owners without emergency procedures was larger for the low consequence class owners than in the higher classes (Figure 4.3). The same tendency was also found for the relationship between consequence class and emergency exercises (Figure 4.4). This result is not very surprising. Many of the dam owners in the low consequence class, which include municipalities and private citizens, lack the resources and competence to follow up legal requirements. The dam owners within the high consequence class, on the other hand, are normally in the other end of the scale with respect to available resources. A general reluctance to adhere to comprehensive official rules may be a reason why smaller dam owners take little interest in emergency planning for dams. Owners of dams in the low consequence class may also get the impression that the guidelines do not apply to them because the guidelines are obviously better suited to larger dam owners, not to mention hydropower companies. It seems as if there is enough evidence for NVE to follow up this survey by finding alternative approaches to emergency planning for smaller dam owners. Offering seminars, as was done in 1995 and 1999, is probably not the best way, as seminars seldom attracts private owners and others with limited resources.

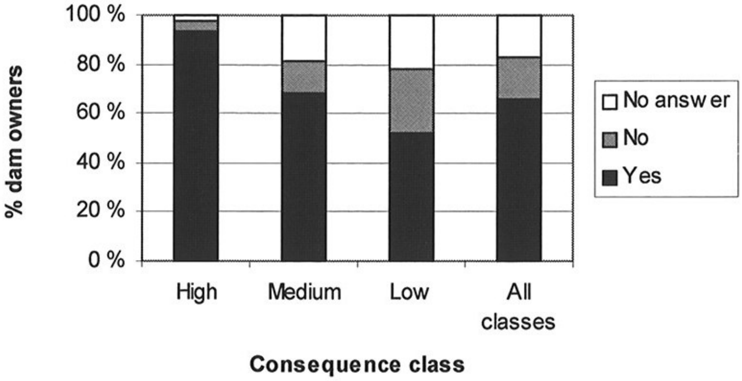


Figure 4.3 Response to question "Have emergency procedures been prepared?"

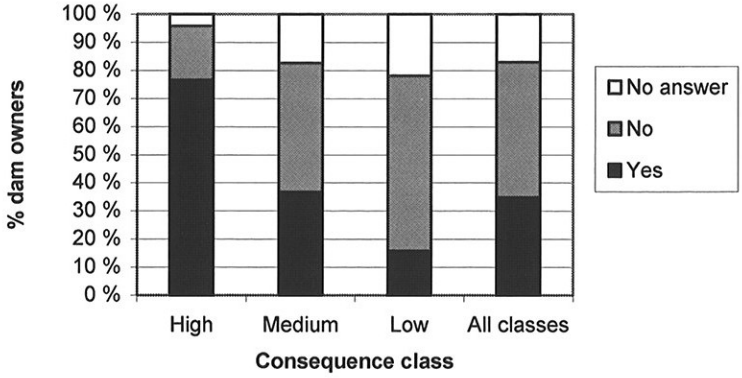


Figure 4.4 Response to question "Have emergency exercises been arranged?"

4.8 Discussion

Even though the threat of war has become less over the last decades in Northern Europe, war cannot be disregarded in our emergency analyses. A "World War II"-scenario is less likely than before, but the terrorist attacks in the USA on 11 September 2001 illustrate future scenarios. An official survey of present status and recommendations for future safety and preparedness activities in Norway (JD 2000) also indicates that our perception of possible threats needs to be changed. According to Langrud (2001) NVE has also recognized the need to pay attention to workforce reductions, as new technology is implemented. All in all, there may be a need to update the present ICOLD guidelines (ICOLD 1987) as well as the Norwegian guidelines on emergency action planning for dams (NVE 1994) to emphasize threats and hazards created by political as well as technological developments. Revision of the Norwegian guidelines on emergency planning for dams should also take into account the findings of the survey presented in Section 4.7.

The survey of the status of emergency action planning among Norwegian dam owners shows that there is still a need for information and assistance. The need is obviously greatest for small dam owner organizations, which have limited resources available (mostly owners of dams in the low consequence class). An efficient way of educating the smaller dam owners may be to use a template for emergency action plans, such as that developed by USBR. The template must be adjusted to domestic conditions and be simple yet cover the most important parts of an emergency action plan. USBR has also emphasized a stepwise approach to emergency action planning (Schuelke 2000). It is important to start by underlining the importance of emergency action planning. A way to encourage dam owners to start developing an EAP may be one of the following:

- Observing or participating in emergency exercises at other dam owner organizations
- Using RIFA
- Participating in emergency handling courses (available from EBL-Kompetanse and NVE)

As many of the smaller dam owners have limited resources, cooperation with larger dam owners is probably the best option, and may even improve cooperation during a real emergency. Larger dam owners performing functional exercises should, perhaps, be encouraged by NVE to invite smaller dam owners in the region as observers. When an emergency action plan is present and approved, NVE should evaluate whether it is necessary to give further advice on the following: planning exercises, coordinating planning with other parties, and updating of the plan. The regular NVE revision of the internal control system may be a suitable occasion for advising dam owners having problems with emergency action planning. An alternative is to offer regional seminars and emergency exercises for several small dam owners, but it is believed this will exclude some dam owners, in particular private owners, from participating unless all expenses are covered.

The emergency analysis is an important element in an emergency action plan. Referring to Chapter 3, the preferred methods seem to be either simple qualitative methods, such as preliminary hazard analyses, or the more comprehensive quantitative methods (typically event tree analyses). When drawing up a new plan, simple methods can be used to evaluate adverse situations. For revision of the emergency action plan or preparation of exercises, event tree analyses may be useful as they include analyses of simple scenarios. The Norwegian regulations point out that during emergency analyses of separate structures it should be noted that some events, typically storms and floods, may have a significant geographical extent and that common cause failures must be expected to occur. As concluded in the previous chapter, traditional risk analysis methods are not tailor-made for analyzing such events in a system of dams, and some method development may be required.

USBR is one of the dam owners that have performed several risk analyses. The results of these are used as an integral part of dam safety decision-making process, among others for prioritization of upgrading between different dams (Cyganiewicz and Smart 2000). According to Schuelke (2000) the results from the USBR risk analyses were not automatically used for improvement of emergency action plans. However, the need to evaluate possible benefits of a closer cooperation between the risk analysis teams and those responsible for emergency action planning within USBR was recognized. Similarly, NVE has recognized the benefit of using preliminary hazard analyses for emergency planning, but it is believed that the issue of integrating risk analysis and emergency action planning for dams should be further emphasized. Indeed, the issue was discussed during revision of the dam safety regulations. It may be timely to bring up the issue again. The regulations for the Norwegian offshore sector are not addressed here, but it is believed that the development in that sector should be looked at as it seems that it has moved towards an integrated approach to risk and emergency analyses (NTS 2001).

5 HAZARD FLOODS – CASE STUDIES

5.1 Introduction

In the search for a better understanding of floods, in particular natural floods verging on the extreme, a confusion of concepts has become apparent. The primary problem is to define levels of floods and particularly to give a good definition of the concept "extreme flood", which is used in many contexts. The issue of defining extreme floods has resulted in, among other places, long discussions within Sub-committee no.3 of ICOLD's committee on "Hydraulics for dams". The members of the committee have for the time being agreed to avoid the term instead of finding an exact definition. Extreme floods have been a topic at several conferences, and one of the latest held in Reykjavik in July 2000, was simply called "The Extremes of the Extremes". One of the presentations in Reykjavik that dealt precisely with the topic was given by Lundquist (2002). Lundquist compares different floods within Norway and other countries. Viewed in this light, Lundquist concludes that the word "extreme" may be defined as "far away from the normal situation in a particular area". Thus, Lundquist concludes further that an "extreme flood" could be defined as an "extraordinary flood with severe consequences for man or nature". In this thesis, "extreme floods" for regulated rivers will be regarded as floods of the same magnitude of or greater than the design flood. For historic floods or floods in unregulated rivers, for which no return period has been assigned, the definition given by Lundquist will be used.

Most scientists, engineers and others involved in safety analyses and emergency action planning have no experience of major floods, not to mention extreme floods. Physical or numerical modeling of floods may provide some insight, but there are limitations with respect to scaling, functionality of administrative systems, the human factor and so on. Thus, in order to be able to cope with floods and ensure the safe operation of dams, a study of previous flood events may provide a useful knowledge base. The process of collecting information is rather time-consuming, which is reflected in the limited number of cases presented here. It is believed that thoroughness is necessary in the search for comprehensive knowledge about extreme floods. The basic idea of this study has not been to collect as many extreme flood cases as possible as represented by peak discharges, water levels or limited descriptions or a combination of these, but rather to find as much information as possible about a few interesting cases. The selection of cases is influenced by the fact that

Vinstra River Basin has been central in other parts of the study, that is there is an overrepresentation of flood cases from this area. Vinstra River (see Figure 7.1) is a major tributary of the Gudbrandsdalslågen (Lågen) River.

Cases from Norway, Sweden (Figures 5.1 and 5.2) and Canada are included. Criteria for selection have been that:

- The flood events be relevant for, but not restricted to, Norwegian river basins
- Cases including those where dam operation was affected be emphasized, especially recent floods, due to their relevance to present conditions
- Extreme floods in unregulated rivers be included to provide information about very rare events
- Where there is information about several similar floods in the same river basin, that with the best data record is emphasized (usually the latest flood)

Of course, not only extreme floods as defined above are included, but also major floods (i.e. less than the design flood) with simultaneous occurrence of adverse incidents causing problems to dam operation. A few flood induced dam failures are included, as well as some examples of post-flood measures for mitigation of future flood damage. The cases are mostly selected on basis of literature study and some relevant overviews from Norway have been found (for example Andersen 1996; Roald 1999). Information about dam failures caused by flood, mostly at small Norwegian dams, can be found in the documentation of the course Dam Safety II (Svendsen 1995). Examples of flood-induced failures of large international dams can be found in ICOLD Bulletin no.82 (ICOLD 1992).

Different sources have been consulted to obtain information about each selected case, such as:

- Journals and conference proceedings
- Theses and technical reports
- Local history books
- Newspaper articles
- Dam operator logbooks and reports
- Official reports
- Eyewitness descriptions
- The author's personal observations and experience

For evaluation of the magnitude of the flood, local flood marks, daily precipitation data as well as discharge or water level records have also been utilized. Sources close to the flood event in time and space (e.g., eyewitness descriptions), and sources covering all aspects of the flood events are emphasized. In addition, official reports are believed to be more reliable than, for example, newspaper articles. Valuable information regarding some of the recent cases has been provided by chartered dam engineers (VTA) within affected dam owner organizations.

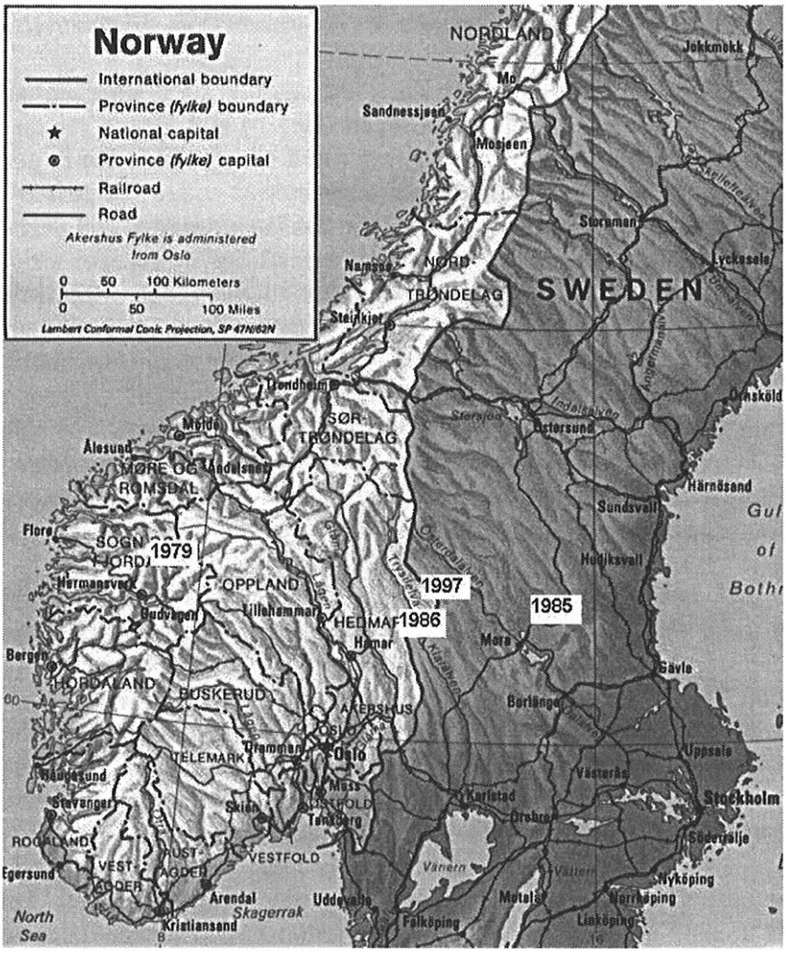


Figure 5.1 Location of the cases River Jostedøla (1979), Ore River (1985), Trysil River (1986) and Stora Göljån River (1997)

5.2 The 1789 flood in southeastern Norway

Langvarigt Regn har holdet ved, Som fyldte alle Elve;
Jordskreder faldt i Mængde ned, Saa Bjerg og Dale skjælve.
Da Engebund Og Agergrund Med Huus og Gaard bordtdrive,
Med saadant Brag, At Dommedag Man vented' skulde blive.

From a poem written in 1789 by a poet in Gudbrandsdalen (Sommerfeldt 1972)

In July 1789, South Norway, particularly the south-eastern parts including the river basins Glomma, Gudbrandsdalslågen (Lågen) and Begna (to the south-west of Lågen), experienced a devastating flood which still is the largest flood ever observed in this region. The flood disaster was called "Storofsen" which may be translated to The Deluge. This flood has been reported and described in several local history books, theses, official reports and newspaper articles (for example Aasnæss 1983; Kjeldsen 1989; Unknown 1938a). Most references cover only parts of the flood event, while a thesis from 1943 (Sommerfeldt 1972) provides a detailed study of the flood and its consequences, summing up most of the first hand references available with an emphasis on Fron district (including Vinstra River Basin) in the valley Gudbrandsdalen. The references used by Sommerfeldt include official studies and reports from the years 1788 – 1815 as well as oral reports from the descendants of people who experienced the flood. The weather conditions have been reconstructed and described by Østmoe (1985).

Several coincidences caused the magnitude of this flood. Large volumes of snow had accumulated in the mountains over the previous years, which had been cold. The autumn of 1788 had been very wet resulting in a high soil water content, moreover, autumn was succeeded by a dry, cold winter, causing deep frost penetration into the ground. After a "normal spring flood" in May fed by snow melting in the lower parts of the catchments, June and early to mid July were dominated by changeable weather. It began as a good year for the farmers with regard to grass production due to fairly high temperatures and frequent rain showers. Then, in the beginning of July the weather changed. The rain-showers became more intense and there were thunderstorms. On the evening of 20 July a severe rainstorm started to build up and reached its peak the following day.

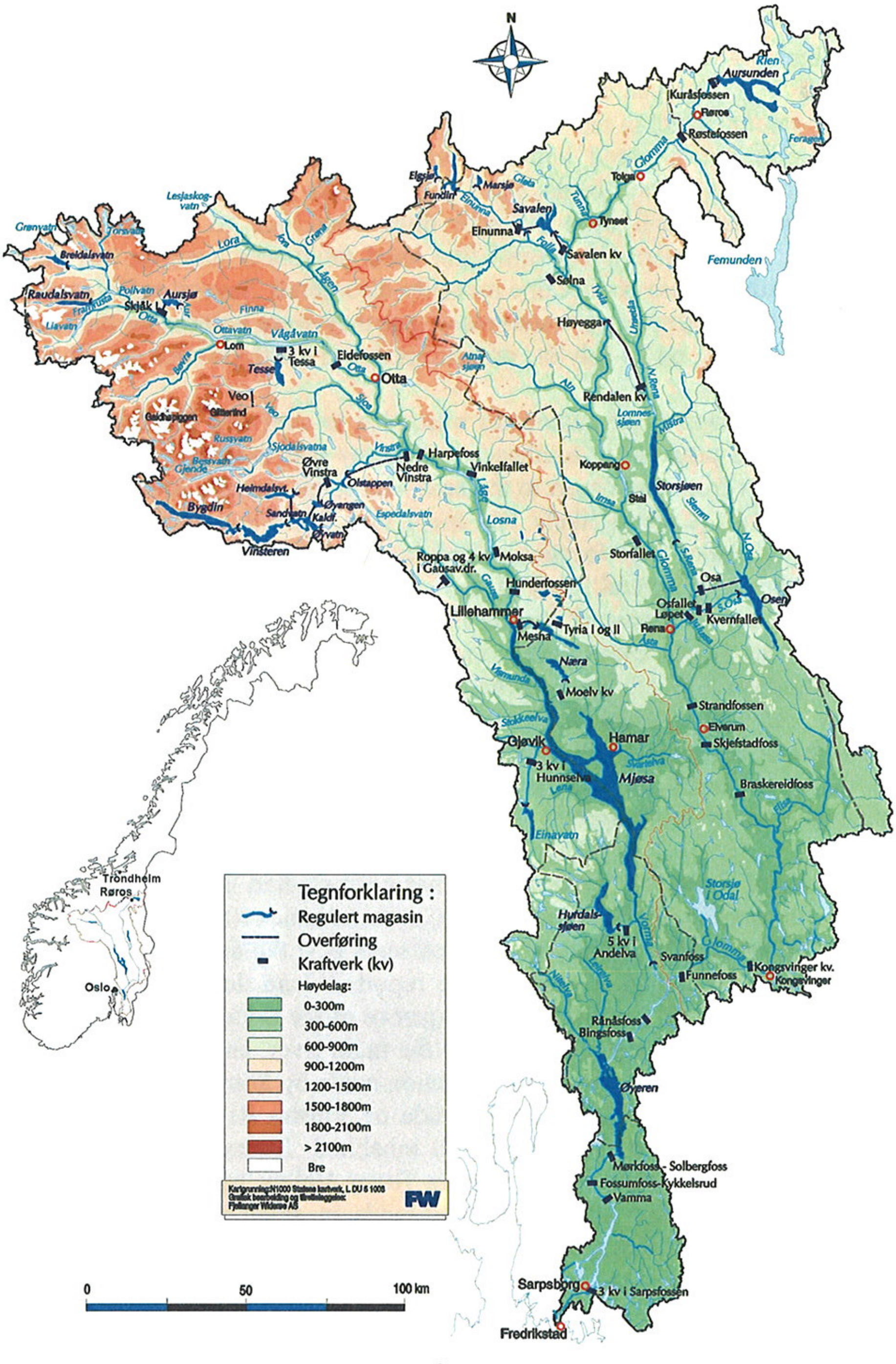


Figure 5.2 Overview of Glomma and Lågen River Basin (Rognlien et al. 1995)

The lightning and thunder was the worst in living memory and daylight never appeared. This weather continued two days with the same intensity. On 22 July, the saturated soil in the steep valley-sides started to slip, and one landslide after the other hit farmland, houses, roads and forests. The rivers and streams, which were eroding their banks and starting to take new courses, sounded like roaring waterfalls and appeared like thick soup due to debris and mud. According to Sommerfeldt, several first hand references mention that people who saw with the disaster became mentally disordered. Several references also report that many people were convinced that they were witnessing the Day of Judgment. Finally, on 24 July the rain stopped, and the flood soon subsided.

After several months, the authorities were able to overview the situation: The loss of life and property in southeastern Norway was extensive. However, the numbers differ from one report to the next, and some damage was probably not registered. Still, it seems likely that more than 3000 houses were destroyed completely, most of them located in Gudbrandsdalen, while 68 people lost their lives together with several hundred each of horses, cattle and other animals. It took many years to recover from the flood and several farms were abandoned. In fact, the flood event even caused people of Østerdalen (east of Gudbrandsdalen) to emigrate permanently to Målselv and Bardu in North Norway. It was reported that debris filled Lake Mjøsa completely and the muddy water destroyed the fish habitats for many years. In Vågå (between Otta and Lom), the local police sergeant reported that he could see more than 60 landslide scars from one spot.

As mentioned above the flood incident has been studied in detail for the Fron district (or *tinglag* in Norwegian) in Gudbrandsdalen (Sommerfeldt 1972). Looking at the Kvikne Parish, which represents best the developed area of the Vinstra River Basin, three people were reported dead due to landslides. No fatalities were reported as a direct consequence of the flood, obviously because the settlements were located high above the main river, as they still are today. According to the very thorough investigation made by Sommerfeldt there were several farms in Kvikne on the north side of Vinstra River from Vinstra to Skåbu in 1789, most of which are still inhabited. Damage to property was extensive and every farm in the Vinstra River Valley had serious losses of fields, meadows, forest and buildings. Floods in small streams and gullies caused erosion, landslides and inundation of land and property. The small tributaries forced their way down the steep valley-sides to Vinstra River. Thus, the general descriptions of the flood given above seem to be very relevant for this area. Total losses for Fron district and Kvikne parish are given in Table 5.1.

Table 5.1. Direct damages and fatalities from Storofsen in Fron and Kvikne (Sommerfeldt 1972).

TYPE OF DAMAGE	FRON	FRON (% OF TOTAL)	KVIKNE	KVIKNE (% OF TOTAL)
Houses destroyed and washed away	492	Unknown	184	Unknown
Houses partly damaged	91	Unknown	3	Unknown
Grinding mills	120	82 %	25	86.5 %
Saw mills	9	50 %	3	100 %
Fields	1584 (10^3 m^2)	26.5 %	621 (10^3 m^2)	45 %
Meadows	11035 (10^3 m^2)	50.5 %	2340 (10^3 m^2)	61.5 %
DEATH TOLL				
People	11	Unknown	3	Unknown
Livestock* (horses and cattle)	105	Unknown	9	Unknown

* Even though direct losses of livestock were fairly moderate, the livestock was dramatically reduced after the flood due to the loss of fodder.

Other available data from this incident are numerous water level registrations (Mølmen 1934), some carved into solid flood stones (Figure 5.4). The water level registered in 1789 at Losna, 188.8 m asl, indicates that the flood of 1789 may have been approximately 6400 m^3/s at this site. This estimate is based on an extrapolation of the official rating-curve for the Losna gauging station. Estimates made by GLB recently indicate a peak discharge of 4500 m^3/s, which corresponds to a water level of 187.5 m asl (Tingvold 2000; Tingvold 2001). According to Tingvold (2001) the explanation to this deviation in discharges, apart from the uncertainty inherent in extrapolation of rating-curves and simulations of extreme floods, is that there would have been a backwater effect between the gauging station at the outlet of lake Losna and the location of the flood stone. An alternative explanation is that the water level may have been raised due to temporary damming caused by the many landslides. In any case, the estimates can only work as a guide to the order of magnitude of the peak discharge of 1789.

Without evaluating the accuracy of the discharges estimated for the 1789-flood, all the registered water levels are clear evidence of an extreme flood. The most seriously inundated area was probably around lake Øyeren northeast of Oslo where the water level rose to approximately 15 m above normal (Hegge 1989). Lake Øyeren had a very narrow outlet in 1789 and as a consequence of the flood it was soon decided to lower flood water levels. At the same time, it was of interest to increase low-flow water levels to improve conditions for log running. The solution finally decided on was blasting to widen the outlet and construction of a dam to maintain the water level for log running. The work started in 1857 and was completed in 1869 (Figure 5.3).

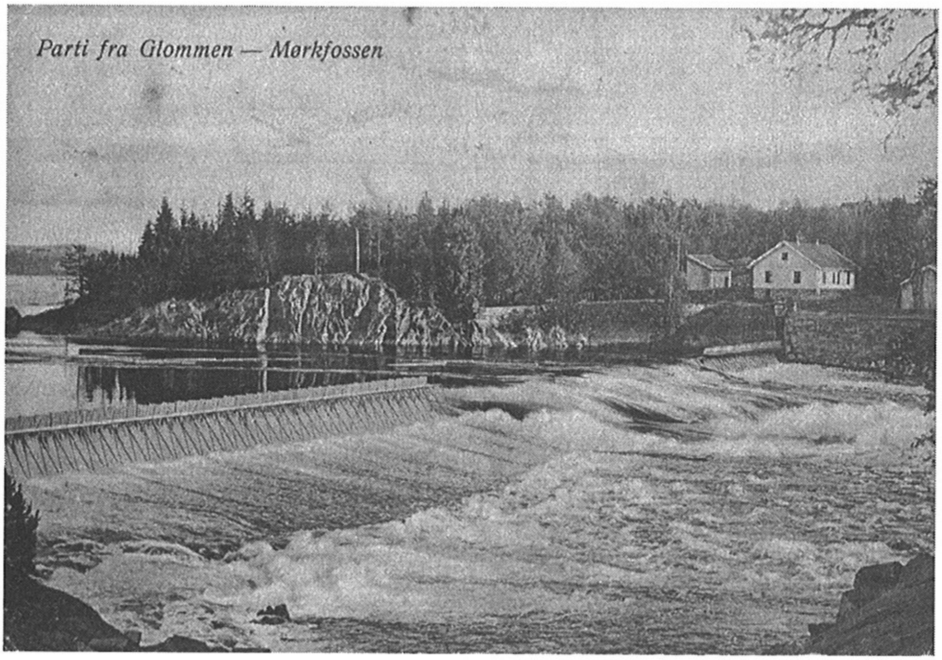


Figure 5.3 The outlet of lake Øyeren at Mørkfoss around 1915 (photo: Mansrud)

5.3 The 1860 flood in southern Norway

The flood of 1860 was another of the largest floods documented in southern Norway. At Lalm, on the Otta River, the registered peak water level was close to the 1789-flood (Figure 5.4) - approximately 10 cm less - whereas the peak water level at Losna in 1860 was 3.5 m below the 1789-level. The flood of 1860 and its consequences are summarized by Roald (2001; 2002). The duration of the flood was exceptional and as a 30-day event the flood had a return period of more than 500 years at Sarpsfoss, close to the coastal outlet (Figure 5.2). The flood volume of the 1860-flood was much larger than the volume of Storofsen in 1789. The peak discharge at Sarpsfoss was 3200 m^3/s

between 24 – 25 June, while the discharge exceeded 2000 m^3/s from 31 May to 8 July. Two flood peaks were observed and the flood affected an area from Vorma River/Lågen in the east to River Skienselv in the west. The flood peaks were caused by heavy rainfall combined with extensive melting of an unusually deep snow pack over a large tract of southern Norway. High volumes of snow are a recognized recipe for a large spring flood, and two months before the flood a local police chief issued a flood warning for River Drammenselv. Even though some measures were taken, the flood caused damage to roads, railways and bridges. Houses were inundated in several places and some houses were carried away by the floodwater. In addition, there were reports of eroded riverbanks and landslides at some locations. Drifting timber also caused extensive problems.

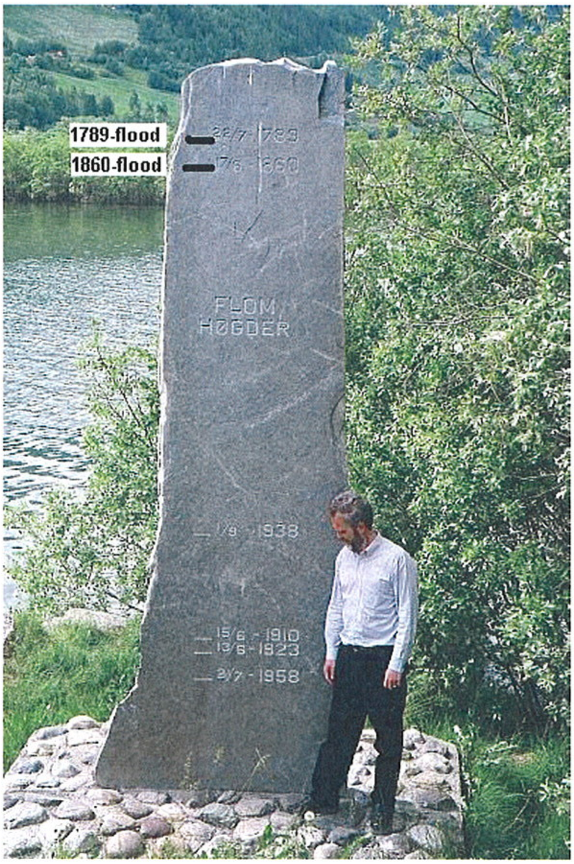


Figure 5.4 Flood stone at Lalm

5.4 The 1938 flood in the Otta, Sjoa and Vinstra River Basins

There were large floods in Glomma River Basin in 1916, 1927, 1934 and 1938, but none of them had the same magnitude as in 1860 and 1789 with respect to extent and damage (Roald 1999). However, in the northwestern part of the Lågen River Basin, the flood of 1938 was far more severe than the other floods in the first half of the 20th century. The 1938 flood is the third largest flood registered on the flood stones at Lalm for Otta River (Figure 5.4) and Losna for Lågen River. The return period in the Bygdin-area has been estimated at 200 years (Beldring et al. 1989).

The summer of 1938 was characterized by an unusually large number of thunderstorms. Even so, on the afternoon of 30 August, people in northern Gudbrandsdalen suspected that the developing clouds would lead to something awful that they had not experienced before. During the next 24 hours, they experienced intense lightning activity followed by heavy rain (Unknown 1938b; Krag 1988; Espelund 1988). The storm caused extensive flooding, erosion and landslides in the steep river valleys of northern Gudbrandsdalen. The inflow to the western catchments also included melt-water from glaciers, which thereby caused extra strain on the river systems. The electricity supply was disrupted along with telephone-lines, roads and railway-lines. The whole region was seriously affected, including Vinstra River Basin, but most damage was reported from Vågå and Heidal in the Otta and Sjoa River Basins respectively (Figures 5.2 and 7.1). The eyewitness descriptions given by Krag (1988) and Espelund (1988) provide a detailed insight as to how the flood affected the local communities of Vågå and Heidal.

The damage reported to roads and property for the Vinstra River Basin were mainly caused by landslides, but small creeks developing into roaring torrents in short time also caused damage. The Vinstra River had not been developed much at the time, except for the regulation of the uppermost lake, Bygdin. Prior to the flood of 1938, the water level in Bygdin was approximately 20 cm below the HRWL and the discharge was kept constant at 1.4 m^3/s until 29 August (Tingvold 2000; Figure 5.5). The dam was supplied with a 4-section spillway (total length = 30 m) closed with vertical beams (Figure 5.6). Additional discharge capacity was provided by one gate in the newly constructed bottom outlet tunnel and two manually operated gates in an old bottom outlet channel.

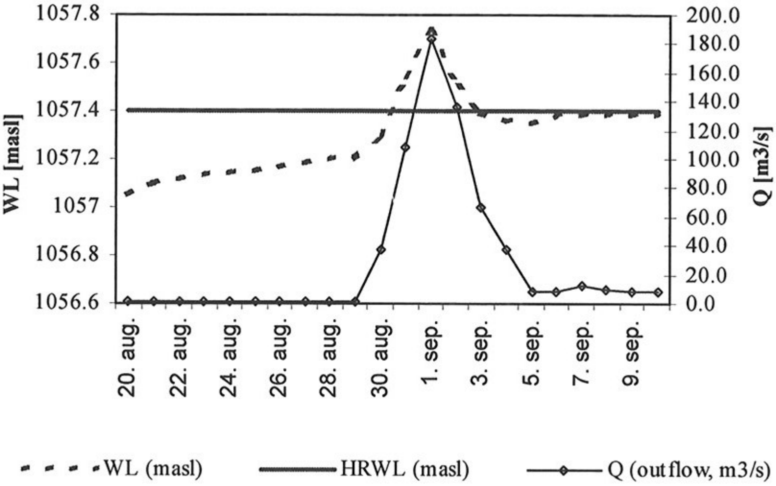


Figure 5.5 Lake Bygdin during the flood of 1938 (GLB)

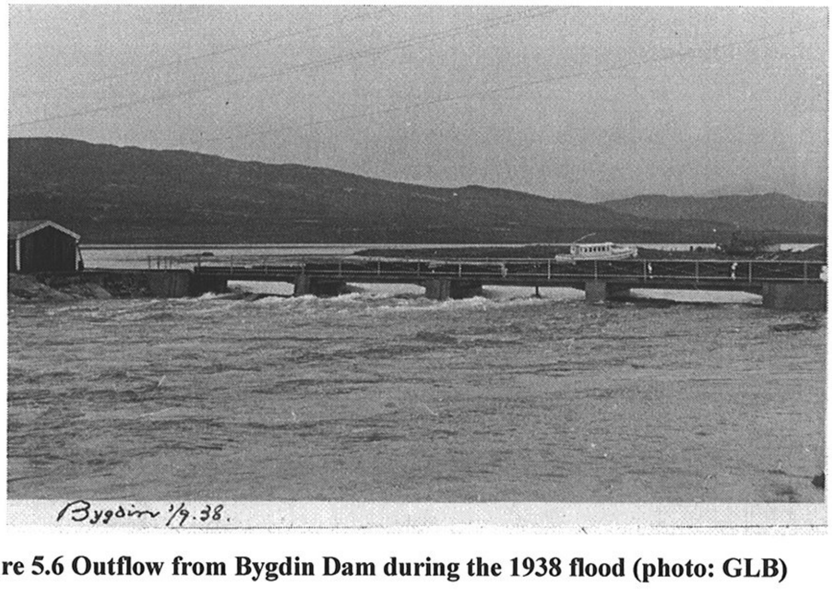


Figure 5.6 Outflow from Bygdin Dam during the 1938 flood (photo: GLB)

The dam attendant started to open the tunnel gate on 30 August at 09:00, but operation was difficult due to disruptions in the power supply (GLB 1938). The dam attendant continued to open gates and remove spillway beams until 13:00 on 31 August. Then the outflow of the reservoir resulted in flooding of a bridge on the downstream road, and the opening of the spillway was stopped to limit damages. However, the water level kept rising and at 21:00 on 31 August it was decided to continue opening of the spillway section. This work was completed at 04:00 the next morning. Maximum water level reached 34 cm above the HRWL, which according to Tingvold (2000) corresponds to a peak outflow of 184 m^3/s (Figure 5.5). Reported damage was mainly caused by erosion of downstream canal-walls and movement of deposited rock (placed along the downstream river during the construction period). The road was closed until 5 September due to erosion (Figure 5.8). Except for loss of spillway beams, which were later found in the downstream lake, Vinsteren, there was only minor damage to the dam structure. Today, the two gates in the outlet channel are removed and the gate openings have been blocked by concrete. The spillway sections with vertical beams have been replaced with a concrete dam with two radial gates. The spillway capacity is almost equal to the capacity of the old spillway.

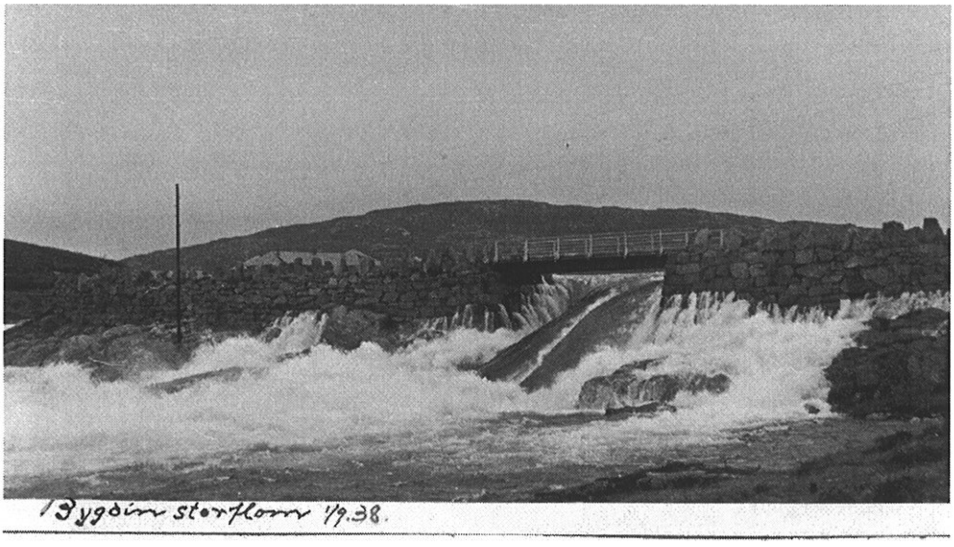


Figure 5.7 Northern road bridge downstream of Bygdin on 1 September 1938, $Q \approx 180\ m^3/s$ (photo: GLB)

Figure 5.8 Damage to southern road bridge downstream of Bygdin (photo: GLB)

5.5 The 1979 flood in River Jostedøla

The drainage basin to River Jostedøla is strongly affected by discharge from the Jostedal Glacier. The total catchment area is 804 km^2 and 29% of the catchment area is glacier-covered. Most of the area is above 800 m asl (70% of the total area) and only a small portion (7.5%) is below 300 m asl (Faugli et al. 1991). Typically, summer floods in River Jostedøla are frequent as a result of glacial melting, and average runoff at Myklemyr is at its maximum during June, July and August (90 – 100 m^3/s). A few flood events have, however, gained distinction, for examples, the floods of 15 August 1898 and 14 August 1979, which have been described by, among others, Bruaset (1996) and Andersen (1996). The inhabitants in the Jostedalen valley were used to glacier-floods inundating farmland at the valley bottom, but these two floods also caused the river to change its course, destroying bridges and roads and eroding away farm land. Trees, deposits (including boulders), and, in 1898, many animals, were taken by the floodwater. Both floods occurred during summer and were caused by warm weather combined with rain. In 1979, there was also a warm thaw wind accompanying rain and high temperatures.

Over 14 hours on 14 August 1979, the water level rose five meters above normal at Myklemyr, which is upstream of the Haukåsgjelet Gorge. The peak level was one meter higher than in 1898. One hundred buildings, 14 bridges and long stretches of the road were damaged (Andersen 1996). Sediments buried a bridge, while another was damaged due to the erosion of a 20 m^3 stone block in the bridge abutment. The flood of 1979 is the largest known of in the Jostedalen Valley. The authorities declared the valley a disaster area and it was two weeks before a temporary road could be built. Despite extensive river works, floods of the same magnitude could still cause considerable damage. The Jostedal hydropower scheme (Figure 5.9), begun in 1984, therefore included flood control in the design of the main reservoir. That is, the filling of the Styggevatn reservoir is restricted (HRWL 1200 m asl). The Styggevatn Dam and reservoir were completed in 1989 (Figure 2.6). The estimated effect of the Jostedal hydropower scheme on flood control is a 10 – 15 % reduction of large floods in River Jostedøla upstream of the confluence with River Leirdøla.

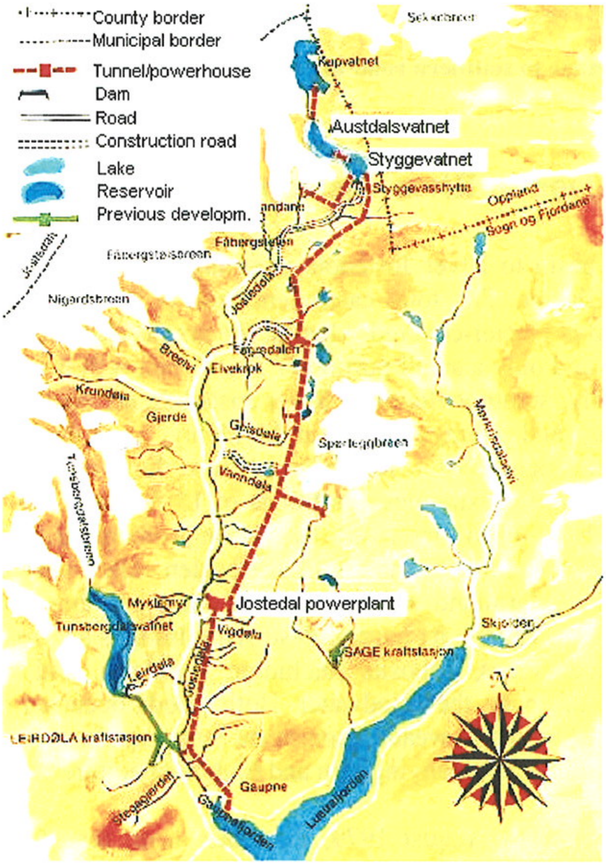


Figure 5.9 Overview of Jostedal hydropower development (NVE)

5.6 The 1985 flood in Ore River, Sweden

The Noppikoski Dam in Sweden failed during a flood in September 1985. The event is described by Enfors and Eurenius (1988) and Skog (1986). The dam and hydropower plant are located on the Ore River, a tributary to River Dalälven, central Sweden (Figure 5.1). Noppikoski is a daily peaking reservoir with a larger storage reservoir located 10 km upstream (Vässinkoski). In 1985 there were no guidelines for determining design floods in Sweden. The practice was to add 10 or 20% to the highest discharge recorded, which was often a flood with a return period of around 100 years (Fridolf 2001). Pertinent data for the Vässinkoski and Noppikoski embankment dams are given in Table 5.2. The power plants were operated remotely; the two operators responsible for the plants and dams were located approximately 20 km from Noppikoski in Furudal.

Table 5.2. Some key data for Vässinkoski and Noppikoski prior to the flood of 1985

	Catchment area [km^2]	Reserv. volume [m^3]	Dam height [m]	Spillway capacity [m^3/s]	Spillway type
Vässinkoski	340	70×10^6	28	95	Inlet: Hydraulically operated gate/ Transport section: Channel
Noppikoski	520	0.6×10^6	18	140	Inlet: Stop logs/ Transport section: Chute

The summer of 1985 was very wet with 175% and 137% of normal precipitation in July and August respectively. The rain continued into the beginning of September and by the end of the month total precipitation was 244% of normal (however, the end of the month was drier than usual!). The water table was therefore unusually high and, together with steep terrain, this caused rapid runoff during the flood event. The flood was in response to heavy rain on 4 and 5 September. All the stop logs at Noppikoski Dam were removed and the gate at Vässinkoski Dam was opened for the first time since the dam was built in 1967. On Friday 6 September, the situation calmed down for a short while. Hence the left spillway opening at Noppikoski was closed completely, and the right spillway was partially closed by one of the four stop logs as continuing rain was forecast. In the afternoon, the dam operator on duty increased the discharge from Vässinkoski from 20 to 33 m^3/s. No changes were made at Noppikoski.

Heavy rain fell later in the evening and the operator was called out to Noppikoski. He was stopped on the access road due to damage caused by streams and was forced to take a 40 km detour. Upon arrival at Noppikoski Dam, the automatic hoisting machine had just started to lift the single stop log in the right spillway opening when the operator observed that something was wrong. The stop log became stuck and the hoisting rods could not be released. This meant that the hoisting machine could not be used to lift the stop logs from the left opening either. The managing engineer was then called out to assist, and while waiting for him, the operator moved to Vässinkoski to increase the discharge further. Meanwhile, the power company's senior enginee tried to hire a mobile crane but this proved difficult late on a Friday night.

Even though it meant a worsening of the situation at Noppikoski, the gate at Vässinkoski had to be opened fully that night, at 01:30 on 7 September. At 02:00 the senior engineer and two other workmen left for Noppikoski to assist with the hoist, but like the operator, they found the drive difficult owing to flooding and damage to the road. Several attempts were made during the night to release the hoist from the stop log, but the staff did not succeed. At 03:23, the district alarm central (LAC) was informed about the situation. Seven minutes later the telephone lines to Noppikoski Dam were broken and further communication was via a radio link. At 04:15, the power plant had to close down due to high water levels and the danger of machinery being inundated. Ten minutes later a mobile crane was reported to have arrived but stopped a few hundred meters short of the power plant on the damaged access road. The senior engineer then realized that the situation was out of control and the dam would fail. Thus, a warning of inevitable failure was issued to the LAC in Falun and an estimate of the maximum discharge to be expected was given along with recommendations for closing of roads. At 05:25 the dam was overtopped and by 06:10, the reservoir was empty. The consequences were visible approximately 20 km downstream of the dam. There was no damage to downstream dwellings and no lives were lost, but two cars and a trailer were claimed by the flood water, some bridges were damaged and the river changed its course over a 2 km stretch causing extensive damage to the forest.

The situation at Vässinkoski Dam remained uncertain even after the failure of Noppikoski Dam and staff had to get there quickly. Some managed to traverse the damaged road with a heavy tractor, and at 07:40, 7 September, more personnel and equipment arrived by helicopter (the helicopter could not fly before daylight). The access road was damaged and telephone lines were broken, but the radio communication functioned well. The Vässinkoski power plant stopped at 08:00 and it was impossible to restart the machinery due to a transmission line collapse. It was decided to open the diversion tunnel to increase discharge capacity because the water level was still increasing. Opening of gates in the diversion tunnel was difficult as described by Enfors and Eurenius (1988), but success finally came on 06:00 Sunday and the discharge was increased to 160 m^3/s. The water level in the reservoir reached a maximum of 88 cm above the upper storage level, and 112 cm below the dam crest. The water level exceeded the top of the impervious core in the embankment and two experts continuously inspected the earth dam during the most critical period.

After the flood, the Noppikoski Dam was rebuilt as a concrete buttress dam, with an extra free overflow spillway crest to increase spillway capacity and new hydraulically operated gates in the ordinary spillway (replacing the stop logs). At Vässinkoski Dam the discharge capacity was also increased by construction of an extra spillway. Several lessons were learnt from this event. Problems tend to pile up during a flood. Impassable access roads were a major problem causing important actions to be severely delayed. Telephone communication and power supply both failed. The inherent safety of gated spillways, and particularly stop logs, is questionable. The combination of gated spillways and dams being vulnerable to overtopping should therefore be subject to thorough assessments. The return period for the actual inflow to Vässinkoski in 1985 was estimated to be in the magnitude of 2000 to 3000 years (Enfors and Eurenius 1988), and the corresponding outflow was estimated to have a return period of 1000 years. Even though these estimates may be uncertain, the flood exceeded the design flood for the dams at that time. Another accidental circumstance is the fact that the critical situation occurred during the weekend, which lessened the possibility of obtaining necessary assistance.

5.7 The 1986 flood, Trysil River

The gate failure at Lutufallet Dam in 1986 is described in detail by Svendsen (1995). Lutufallet is a run-of-river hydropower plant with a 10-meter high embankment dam with a concrete core. The dam is supplied with two spillway gates, one sector gate and one radial gate, in addition to a free overflow section. The intake and the power station are located at the eastern abutment. On Friday 9 May, during a 10-year flood, the sector gate was open and the power station remained in operation. The radial gate was operated frequently to keep the headwater at a constant level. During cleaning of the trash racks the automatic operation of the radial gate was disconnected and the operator tried to operate the gate from the control room in the power station, but nothing happened. A visit to the gatehouse revealed that the motor protection was set in motion, but even though the motor was somewhat warm, the operator was not worried. The motor protection was disconnected and the radial gate was hoisted. After a few seconds the operator heard a bang and the gate fell. Later it was found that both lifting bolts had broken. It was impossible to lift the gate. The water level increased as a result of the sudden closure of the gate, the dam was in danger of overtopping and the powerhouse of inundation.

The dam owner tried to obtain mobile cranes to lift the gate, which was difficult as Friday 9 May was the day after Ascension Day, a public holiday in Norway, and many people were off work. Finally, three 20-ton mobile cranes arrived, but in the interim water had risen above the radial gate and it was not possible to fasten wires or hooks to the gates. It was concluded that controlled blasting of a part of the embankment dam would be the best option in order to minimize the effects of the flood. The army was contacted to assist in lowering the water level by controlled blasting of the crest of the western embankment (Figure 5.10).

Figure 5.10 Preparations for blasting of western embankment during the 1986 flood at Lutufallet (photo: O.J.Olberg)

The blasting was successful and the water level decreased immediately, but due to heavy precipitation during the night, the water level increased the next morning. The army was again asked to assist. After having struggled with unexpectedly strong concrete, they managed to enlarge the blasted hole in the concrete core of the embankment section and thereby increase the discharge capacity. Unfortunately, the water level did not lower due to the increased flood discharge in the river, but the situation was under control.

The power company contacted Kværner Brug (an engineering workshop) and personnel soon arrived with clamps to be fastened to the gate. However, the clamps were not fastened as there was water flowing over the top of the gate. Eventually, a diver from Kværner managed to fasten straps to the gate. Attempts were made to lift the gate with the mobile cranes, but the lifting capacity was insufficient. Another mobile crane (50 tons capacity) was ordered from Oslo. The blasting of the western embankment, which also served as the access road, meant that the mobile crane had to be re-routed by approximately 200 km, via Sweden, to the radial gate. Thus, the mobile crane did not arrive until Sunday morning. Finally, two days after the accident, the gate was lifted bringing the situation under control. The water level was lowered three meters immediately. Luckily, the only damage downstream was some erosion of the road. Even though the dam owner had to sacrifice parts of the dam, the much more valuable parts of the power plant were saved.

Lessons learnt from this event are among others that several unforeseen events can slow extremely important operations severely during an emergency. Acquisition of equipment and external resources may be difficult, especially when emergency situations develop outside of normal working hours, even more so during holidays or weekends. In this case, an emergency spillway could be opened as a result of blasting of the embankment, even though the embankment was not designed for this purpose. Blasting would probably have been less successful without the assistance from the army. This event demonstrates that emergency spillways should be considered at dams vulnerable to overtopping.

> *From Aftenposten 16 May 1986: "The main road between Trysil and Sweden was blasted last weekend to release flood water threatening Lutufallet power plant. The blasting has proven to be extremely successful. Very few Swedes have been observed west of Trysil recently and several similar blastings are planned in Southeast Norway in the near future."*

5.8 The 1987 flood in southeastern Norway

During 16 and 17 October 1987, most of southeastern Norway experienced a rainstorm, which caused a severe flood. The previous 30-day period was characterized by heavy precipitation, up to 240 % of normal, which in the higher altitudes came partly as snow (Engen 1988). The maximum 1-day precipitation during the 2-day rainstorm was 97 mm with a corresponding return period of 10 – 15 years. The return period for the resulting flood was up to 100 years in some areas as shown in Figure 5.11. The rainstorm was combined with strong wind velocities of up to 30-40 m/sec. Reservoir filling was nearly 100% in all affected reservoirs and consequently most of the floodwater had to be by-passed during the flood. The coastal areas affected by the rainstorm also experienced storm surge, which further increased the total damage. The highest seawater elevation observed was in the inner parts of the Oslo Fjord and particularly in the branch Drammens Fjord.

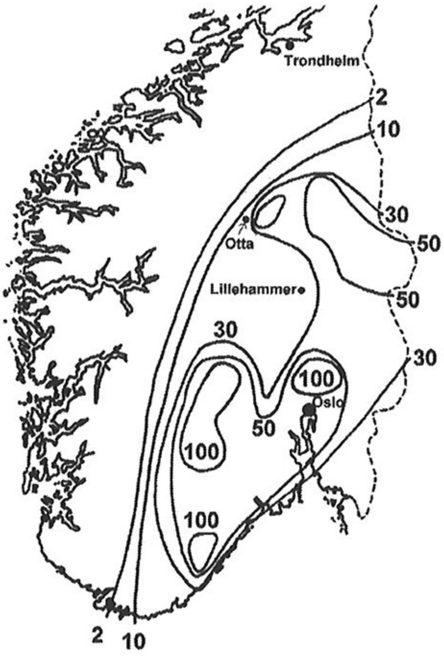


Figure 5.11 Return period for the 1987 flood in South Eastern Norway, compared to 1-day autumn floods (Engen 1988).

The rainstorm caused periodic disruptions to telecommunication lines, power supply and road connections. Problems with flood diversion and damage to dams were reported, dams with gated spillways being the most affected. Dam owners were generally able to take action in due time to prevent dam failures, but in some cases they reacted too late or did not even visit the dam until flooding had ceased. Some small dams were overtopped, but only two dams failed. The first was small and resulted in insignificant damage. The failure of the second dam (Kjøljua), which was not completed at the time, caused some damage to construction equipment.

NVE made an inquiry into flood related problems after the situation had calmed down. The results from the inquiry are reported by Svendsen (1989). Sixty-four dam owners, representing 365 dams, responded to the inquiry, and an overview of typical problems encountered is given in Figure 5.12. Access roads were impassable due to inundation, erosion, fallen trees and landslides. In some cases dam owners were able to pass with 4WD cars or by driving or walking long distances along alternative routes (such as small local roads used for forestry). Power failure was caused by broken transmission lines, and in some cases, by clogging of intake trash racks causing production to stop. Major problems were avoided to a great extent due to the fact that most gated spillways were already opened. Many dam owners were also equipped with an auxiliary power supply from diesel units or had the opportunity to manually operate the gates. However, auxiliary power proved to be unreliable and manual operation of gates was slow and required a real trial of strength.

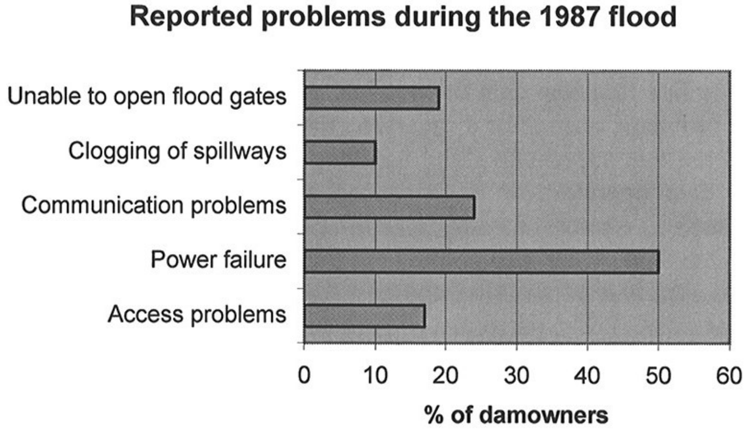


Figure 5.12 Typical problems reported during 1987-flood

At Braskereidfoss Dam, a critical situation developed due to malfunctioning of the auxiliary power supply. The dam, which is part of a run-of-river hydropower plant, had been analyzed a short time prior to the flood as part of a project on risk analysis for dams (NVE and VR 1987). The risk analysis revealed that the worst case-scenario for this dam, with respect to upstream water level control, was an increase in water level from HRWL to the top of dam crest (i.e. 1.7 m) in approximately 13 hours. During the 1987-flood the dam owner experienced an increase of 1.4 m from HRWL in one hour and five minutes, as he could not operate the gates without a power supply. Luckily, a driver working for the hydropower company located the failure in the auxiliary power supply unit and managed to start it. Thereafter the spillway gates could be opened and the situation was under control.

In many cases gate operation was obstructed by debris (see Figure 5.13) and in some cases by high water levels (due to slow reaction to the developing flood). Debris and high water levels were not the main problems for the dam owners, but they caused the most serious challenges. In one area large amounts of debris entered the river from landslides in steep valley sides along the river. The sliding occurred in a forested area and was triggered by clogged ditches along a newly constructed forestry road on top of the steep hill. Telecommunication problems were mainly a concern for dam owners with several dams and dam personnel distributed over a large geographical area. Some were unable to monitor water levels and keep contact with personnel, thus it was difficult to assess the need for immediate action, allocation of resources and so on. Damage to dams mostly appeared at slope protection and crest of embankment dams, spillways, and walking bridges hit by debris.

In spite of the fact that few dam owners had emergency action plans in 1987 many of the problems were solved satisfactorily by improvisation. Several dam owners reported that successful flood handling had not been possible without experienced dam operators or extra personnel and easy access to suitable equipment (such as tractors, forestry machines and so on) or a combination of these three. One dam owner also pointed out that practical experience from gate operation (on site) was extremely important for successful operation given the circumstances (storm). The personnel of another major dam owner organization later referred to the 1987 flood as a stressful and unpleasant experience. The dam attendants operated alone on different dams in the mountains (Molle 2001). Registration of water levels and operation of spillway gates had to be done manually during the middle of the storm. Luckily, there were (and are) houses for dam attendants near all the dams in this river system. The attendants lost communication with the control center and felt uncertain about what they should do. The dam owner used the experience to improve communication systems and to develop emergency action plans. Other dam owners decided to upgrade their dams to be prepared for future floods of the same severity as that in 1987.

One example of dam upgrading is the arch dam Vinkelfallet, a high-consequence class dam north of Lillehammer completed in 1984. There is a vulnerable vertical soil zone adjacent to the left abutment with a small embankment dam on top of this zone. Originally, there was a footbridge on pillars over the free overflow spillway crest. During the flood in October 1987, several other dam owners in the region experienced serious problems with clogging of spillways as mentioned above. The management of Vinkelfallet dam had observed some landslide activity at the upper end of the reservoir, which could potentially have brought debris (including large trees) into the reservoir. Thus, it was decided to remove the bridge and pillars over the spillway crest to allow debris to pass safely without causing hazardous, unwanted high water levels. Clogging of the spillway could, at worst, lead to an overtopping of the small embankment dam, a situation the dam owner wanted to avoid. After the spillway was upgraded, the dam owner experienced a flood that exceeded the 1987 flood locally, see Figure 5.14. The dam engineer stated that he felt very comfortable about having removed the walking bridge before this flood.

One lesson learnt from the 1987 flood was that floods caused by rainstorms in combination with strong wind make it difficult to perform emergency actions on the dams. In addition to the hazards normally connected with floods, such as erosion and inundation, strong wind could cause trees to fall in the forested areas and may make it difficult to move around in open areas, such as at a dam site in mountain areas (above the tree line). The prevailing weather conditions of 1987 also made it impossible to use helicopters as alternative transport in areas with damaged access roads. Moreover, communication was hindered, and radio communication (closed systems) proved to be the best option in many cases. The large amounts of debris were a useful reminder of the vulnerability of gated spillways, and especially spillways with stop logs. One must remember also that this flood occurred at a time when official flood forecasting was not established fully. In other words, many dam owners had a very limited timeframe to take necessary precautions, such as early opening of spillway gates. Emergency action plans were in most cases not developed, but some dam owners had prepared emergency procedures. The presence of adequate resources (including experienced dam operators) was one of the important factors for successful flood handling.

Figure 5.13 Debris at small intake dam, 1987 (photo: V.N.Svendsen)

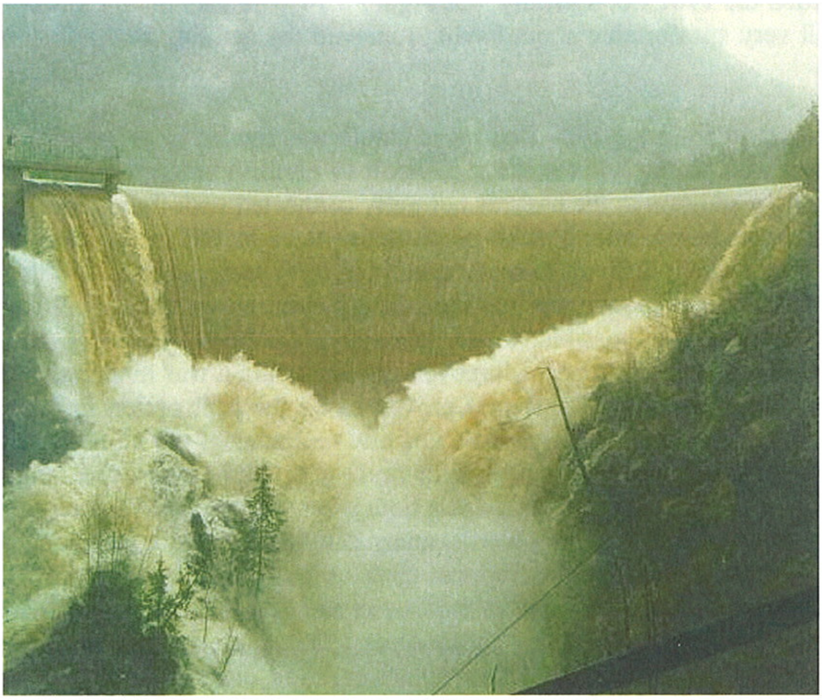


Figure 5.14 Vinkelfallet Dam during spring flood in 1992 (photo: T.Skarstad)

5.9 The 1995 flood in southeastern Norway

5.9.1 General description of the event

In May and June 1995 southeastern Norway experienced a flood, which at several locations almost reached the level of the famous 1789-flood "Storofsen". The 1995 flood was therefore soon known as "Vesleofsen" ("the small Deluge"). The most affected areas were within the Glomma and Lågen River Basin and the Trysil River Basin, to the east of Glomma River. Glomma and Lågen River Basin alone has a catchment area of 41 200 km^2 and covers 13% of the total land area in Norway (Figure 5.2). The mean annual runoff from Glomma (including Lågen) is 22 000 million m^3 and total reservoir capacity is 16% (3 568 millions m^3). The largest lake, Mjøsa, has a reservoir capacity of 1 312 millions m^3. There are two main rivers, Glomma and Lågen and fortunately, as there was flooding over the whole catchment in 1995, the flood peaks from the two branches did not coincide at the confluence (see Table 5.3 and Figure 5.2). The flood is evaluated and described thoroughly in an official study (NED 1996). The organization responsible for coordination of reservoir operations in the entire Glomma and Lågen River Basin, Glommen and Lågen Water Management Association (GLB) has issued a separate report covering the essential features of the flood (Lundquist et al. 1996). The GLB-report describes the period prior to the flood, the preparations made, flood forecasts, flood propagation and how the media covered the flood. The report includes many facts about this flood and comparing data from historical floods. The descriptions given in this section are also partly based on the author's own notes from inspections during and after the flood at the Bingsfoss, Solbergfoss and Vamma dams and power plants, as well as the Lågen and Moksa rivers and Vinkelfallet Dam. Experience gained by the author from the emergency action group in NVE during the most intensive period of the flood is also utilized here.

At the end of April 1995, snow storage was 130-150% of normal and GLB started preparing for a possible large melt flood. Pre-release of water from reservoirs was discussed with the authorities and was done at some reservoirs. Long-term predictions were made on basis of historical weather data and some scenarios prepared on 16 May showed a flood peak of more than 4 m above the highest regulated water level in Mjøsa around 10 June. Until 22 May temperatures were low and consequently snow melt was delayed. Then temperatures increased by 5 – 10°C and snow melt started. From 25 May to 2 June, approximately 4 000 million m^3 of melt-water was released corresponding to 100 mm precipitation over the whole basin. In addition to snowmelt, there was 50 to 70 mm of rain between 28 May and 2 June over the central parts of the catchment. The most affected was the mountain area between the valleys Østerdalen and Gudbrandsdalen, and this is also the area where the most severe incidents on dams and power plants occurred.

Table 5.3. Estimated peak discharges at some locations during the 1995 flood (Lundquist et al. 1996; Tingvold 1999).

Location	Catchment area [km^2]	Peak discharge [m^3/s]	Date
Glomma at Barkaldfoss (south of Høyegga)	6 600	1 400	2 June at 22:00
Glomma at Stai	8 900	2 000	2 June at 18:00
Glomma at Elverum	15 356	3 350 – 3 400	2 June at 19:00
Glomma at Funnefoss	20 390	2 900	4 June at 17:00
Otta River at Lalm (upstream Eidefoss)	3 980	705 - 715	3 June at 12:00
Lågen at Losna	10 990	2 400 – 2 500	3 June at 19:00
Mjøsa (at the outlet of the lake)	17 570	1 600 – 1 650	11 June at 20:00
Glomma at Rånåsfoss	38 260	3 800 – 4 000	5 June at 05:00
Øyeren (at the outlet of the lake)	40 013	3 570 –3 580	6 June at 23:00

GLB applied to NVE to be allowed to deviate from their normal operational procedures in April and early May to prepare for snowmelt runoff. On 19 May, the danger of severe flood was so obvious that GLB also applied for dispensation from licensing conditions for the Osen Reservoir in order to increase pre-release. The pre-releases from the regulated reservoirs paid off. GLB has estimated that the effect of flood mitigation for reservoirs on Glomma River upstream of Elverum was a reduction of 800 m^3/s of the peak discharge (Tingvold 1999). Without the reservoirs, the 1995-flood would have peaked at a water level above the 1789-flood at Elverum. For Lågen River, flood mitigation led to a reduction of 325 m^3/s of the flood peak at Losna. Luckily the melt flood from Otta River was delayed in comparison to the flood peak in

Lågen, and excessive damages for Lågen and Mjøsa were avoided. In addition, there was, in general, a modest contribution to the flood from the western tributaries of Lågen. At Solbergfoss Dam, downstream of the lake Øyeren, the flood mitigation effect of all the upstream reservoirs and other flood mitigation measures was a reduction of 700 m^3/s of the flood peak.

5.9.2 Flood forecasts and media coverage

GLB and NVE cooperated closely with flood forecasts during May, as they were aware of the threat of flooding. During the flood, however, there was some "disagreement" about estimated probable peak levels, resulting in press releases from both GLB and NVE with deviating estimates of peak levels. Of course, flood forecasts are inherently uncertain. Different weather forecasts may be difficult to handle and it may be difficult to anticipate flood effects (for example dike-failures), which are not considered during calibration of the hydrologic and hydraulic models used for flood forecasting. The accuracy of the models used will also influence on the output. In any case, the different flood forecasts from GLB and NVE were first and foremost a problem for those responsible for public safety, media and residents in the affected area. Another problem reported after the flood, was that the first flood warning from NVE to the dam owners was sent as an ordinary fax, which did not attract attention. One dam owner later found out that nobody in their company had responded to the first warnings (Brox 1995). A similar problem (of "anonymous" faxes from the authorities) was also reported with respect to instructions for establishment of emergency action groups.

The first warnings of a possible flood was issued by NVE on 9 May 1995, and on 26 May NVE issued an official forecast of "major flood"(NED 1996). According to Lundquist et al (1996) GLB recognized the threat of an extreme flood on 19 May. From 29 May, the alert level in GLB was increased gradually, and subsequently the different power companies (and dam owners) did the same. NVE increased their alert level more or less in parallel to GLB and an emergency action group was established by NVE on 1 June. Luckily, GLB, NVE and Vinstra Power Company had a joint emergency exercise in autumn 1994 (see also Section 4.6.2). The selected scenario was "a considerable flood at the same time as personnel on duty were missing". Even though pressure from media played an important part in the emergency exercise in 1994 and many of those involved in the management of the 1995-flood should have been prepared, the real situation in 1995 was overwhelming as described by Lundquist et al. (1996). Journalists hunted for the best headlines (i.e. "disasters") and photographs. Nobody was interested in writing about the preparatory lowering of the headwater at Solbergfoss and other power plants. Instead there were dramatic headlines such as the “flood war” between the cities of Lillestrøm on Lake Øyeren and Hamar on Lake Mjøsa. Worth mentioning though, is the positive attitude in the local radio stations in assisting with distributing information to the local communities desperately fighting to save houses and villages.

5.9.3 Effects on dam safety

The emergency action measures taken during the flood are reported for several power plants (Brox 1995). The report is mainly based on visits to the power plants and gives a sort of “first impression”. NVE also made an inquiry into problems related to dam safety during the flood of 1995 as reported by Grøttå (1995). Letters were sent to 15 dam owners in August 1995, of whom all replied. The geographical area covered by the inquiry was the Trysil, Glomma and Lågen River basins, which contain 51 dams. Several dam owners experienced discharges and water levels in the same order of magnitude as the design flood (see Figure 5.15 and Appendix B). One power plant in Glomma was exposed to inundation hazard due to dangerously high water level at an upstream dike. The dike was close to failure, but luckily it withstood the flood. Two events are described separately below: the failure of Tippskaret Dam on a western tributary to Glomma and the disaster at Tretten where the Moksa River took a new course.

Due to the problems caused by debris during the flood of 1987, one might expect that this would also have been a problem in 1995, but such problems were reported from one dam only (Grøttå 1995). This dam located on a tributary to Glomma had spillway openings with horizontal stop logs and vertical beams respectively. One stop log opening in the spillway was clogged by debris but the rest of the spillway functioned well. The trash rack at the power plant intake, however, had to be cleaned regularly due to clogging. The author observed much debris and trash in the rivers during and after the flood (including a building floating in Lågen) with potential of causing problems. Debris was reported as a general problem for power plant intakes (Brox 1995), most of which were cleaned efficiently. One dam in Trysil River reported receiving warnings of a large barn floating down the river. The dam owner feared the barn would damage the dam or clog the spillway gate openings, but the building was torn apart before it arrived at the dam. In most cases, debris was probably transported through the large spillway openings. In addition, the flood developed slowly in the main rivers and all spillway gates were probably open already when debris were mixed with the water flow.

Apart from the incidents mentioned above and the risk of overtopping and inundation of one dam and power plant, there were no reports of severe technical problems in the inquiry related to dam safety (Grøttå 1995). Some damage caused by erosion was reported from several sites. There is a mismatch between Brox's report and the responses to the dam safety inquiry with respect to technical problems. A possible explanation is that typical problems reported by Brox (1995) were related to the power plants, such as high tailwater-levels (Figure 5.16) and inundated staff gauges or failed electronic recording instruments. In cases where problems could cause the power plant to shut down, increased discharge through the spillway would ultimately be the result, and the safety of the dam might be affected. Still, this aspect has not been emphasized by the people who later responded to the dam safety inquiry, as reported by Grøttå (1995). One possible explanation is that different people responded to the respective reports. Another may be that the inquiry reported by Grøttå was performed some time after the flood while Brox's report was based on visits to the power plants during the flood. The time delay between the two may in some cases have lead to suppression of facts, especially unpleasant ones.

Grøttå reports that 10 out of 15 dam owners had prepared emergency action plans prior to the flood, and the general impression was that this was beneficial during the flood (Grøttå 1995). At the same time, the flood experience gave the dam owners useful input to their emergency action plans. The reports from the dam owners had comments on preparedness and emergency action planning, such as:

- If possible, the emergency actions group should be similar to the organization as it appears during normal operation
- When necessary, the emergency group leader should have the possibility to organize ad hoc-groups to solve particular problems
- Information should be exchanged regularly within the organization, preferably through meetings
- The dissemination of information is extremely important due to pressure from media, the public, authorities and personnel. Extra personnel may be needed to handle information efficiently

The comments given here comply well with the comments found in Brox's report, and also with the author's own experience from working at NVE during the flood.

Figure 5.15 Peak discharge at Vamma Dam during 1995 flood

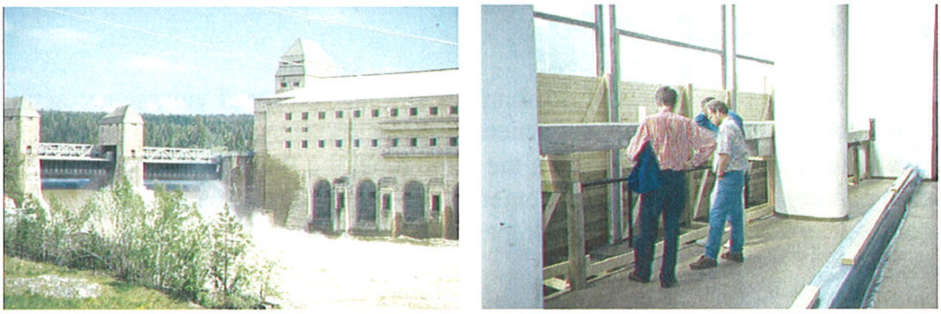


Figure 5.16 Solbergfoss Dam and powerplant - protection of machine hall against high tailwater level, 6 June 1995, Q≈3500 m^3/s

The long duration in combination with the floodwater volume, especially for the main rivers, may have caused strain over and above normal on key personnel. The shorter, but more intense events in some of the tributaries may also have caused extra strain. In a few cases, key personnel were so overloaded with responsibility that they nearly collapsed (Molle 2001). This should be taken as a serious reminder of the need for qualified substitutes in case of long lasting emergencies, emergencies with a large geographical extent or emergencies with very severe consequences. Another problem is simply the possibility of key personnel being on holiday, or unavailable for some other reason. Indeed, this was the case within at least two dam owner organizations when the flood started to develop. It should also be kept in mind that human response to emergencies may vary and that the critical level for one person with respect to coping with an emergency may be far beyond that of another person. Finally, the ability to improvise, and thereby solve problems as they arise, seems to be related to the personnel's experience and knowledge about their facilities and emergency handling. Similar findings to those described above for people securing flood levees along the main rivers are reported by Krasovskaia et al. (2000).

An unexpected problem at some dams, especially in lower reaches of Glomma River, was incredible interest from curious visitors. "Flood tourists", or rather "disaster tourists" are not a new phenomenon. As an example the unusually large flood in River Nidelva, May 1934, drew a crowd of approximately 10 000 in one day to Nedre Leirfoss Dam and power plant to watch the impressive waterfalls (Adresseavisen 1934). Whether this was a problem to the dam and power plant operators at Nedre Leirfoss is not known. The flood tourists in 1995, however, often hindered the dam personnel by blocking bridges over spillways and access roads and so on. In addition, they potentially risked their own safety by "crawling" along the riverbanks while the flood eroded beneath their feet. An example from Solbergfoss illustrates the tremendous desire people had to see the flood. Many people arrived by cars via the narrow access road from the west to Solbergfoss Dam. The bridge over the dam had to be closed for vehicles during the flood because of the traffic burden. Even a large bus took a detour from highway E18 along this road to see "the incredible flood of the century"! Several dam owners had to ask from the civil defense, the army or local police for assistance restricting admittance to the power plants and dams. The army also assisted with various flood mitigation measures at the dams and power plants, such as filling of sand bags.

5.9.4 The disaster in Moksa River, Tretten

Most people involved or interested in the flood of 1995 will know of the disaster at Tretten that occurred when Moksa River suddenly changed its course. Photographs from Moksa were on front pages of most newspapers and television news in Norway for days after the disaster. Some blamed the power company, Midt-Gudbrandsdal Energi (MGE), the owner of Moksa power plant, for the disaster. Norges Miljøvernforbund, a non-governmental environmental organization, filed a lawsuit against MGE for having narrowed the river. However, the case was later turned down. No narrowing of the natural river course had taken place. The presence of MGE's facilities in the area (such as power plants and river training works) had probably delayed the development of this unavoidable disaster. Some photographs from the disaster are provided in the text below, more are available in Appendix B.

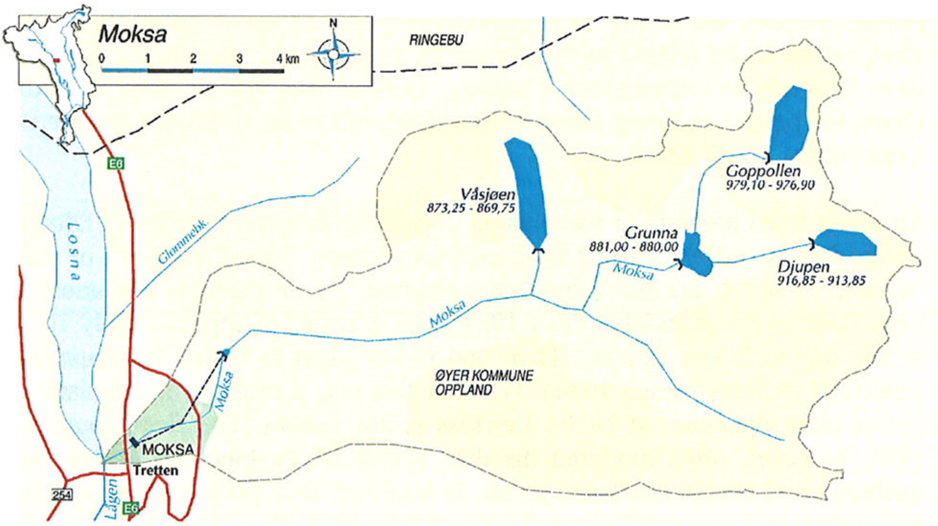


Figure 5.17 Map of Moksa River Basin with Moksa power plant at Tretten (GLB)

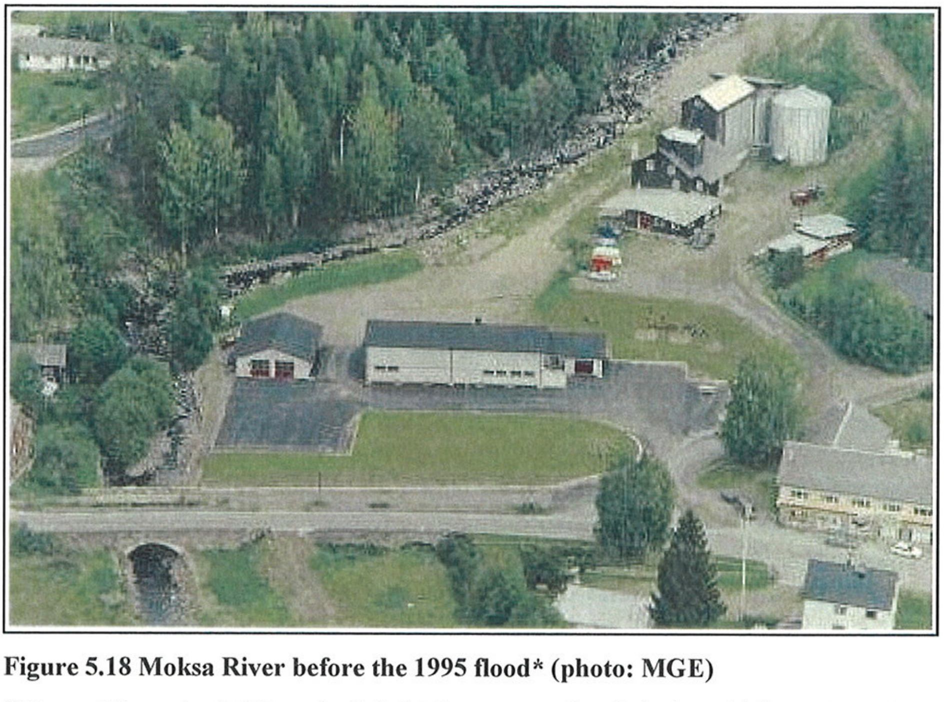


Figure 5.18 Moksa River before the 1995 flood* (photo: MGE)

* Fonstad is partly visible to the left, Moksa power plant is in the middle, and Stavheim mill is in the upper right corner.

MGE owns and operates hydropower facilities, not only on Moksa River, but also on Våla River at Ringebu, 30 km to the north of Moksa River, both are tributaries to Lågen. On 30 May, MGE had already observed major discharge of around 165 m^3/s from Vinkelfallet Dam on Våla River (Skarstad 1995). Discharge decreased slightly the following day, but there was still a need for regular inspections and monitoring of the situation at the dam and along the river downstream. The chartered dam engineer (hereafter referred to as VTA) at MGE was concerned about the development at Vinkelfallet Dam, but he soon had to concentrate on other problems. On the morning of Thursday 1 June, the mechanical engineer at Moksa power plant called him about increasing discharge upstream of the power plant. The river runs over an old alluvial fan where the power plant, a mill and some other buildings were located (Figure 5.18). Thus, erosion from a large flood was a potential hazard. The VTA and the managing director (MD) went together to Moksa and arrived at noon.

Strengthening of the riverbanks started as soon as was possible with an excavator. Due to the difficulty of obtaining enough stone blocks, trees were tested with stones. MGE was most concerned about erosion in two areas; close to the old power plant Moksa 1 (see Figures B-1 and B-5), which is located above Stavheim mill, and in an area around the old highway bridge where a large house (Fonstad) was in danger (see Figure 5.19). In the afternoon, at the same time as erosion protection works were carried out on the riverbank, the VTA tried to contact the local police to inform and discuss the situation. The local police was busy elsewhere, so the VTA called the police at Lillehammer instead. The Lillehammer police gave MGE authority to do whatever they felt necessary to mitigate the effects of the flood. At 18:00 they found they had to concentrate on securing the power plant and informed the local authorities that they could not secure Fonstad.

At 19:00 VTA received a message from Vinkelfallet Dam saying that the spillway had been overtopped by1.8 m (this was later corrected to 1.4 m). The rating curve indicated an unbelievably large flood! The VTA was very worried, and soon after a new message said that Vinkelfallet power plant had shut down. The VTA had to stay at Moksa, and the mechanical engineer left for Vinkelfallet. Meanwhile the situation at Moksa developed and became more and more threatening. Many people had gathered in the area, and the excavator driver became even busier. A property owner near Moksa 1 rushed to Moksa power plant saying that the river were flowing onto his land and his house was threatened. The MD took care of the property owner while the VTA ran to overview the site. Fortunately, the water had found a new course in the meantime, directed away from the house. Within the next few hours the VTA called back the mechanical engineer from Vinkelfallet to Moksa. A senior engineer passing nearby on his way home from holiday was also asked to make a stop at Moksa. At 22:00, the engineers at Moska were informed that the main road through the valley (E6) would be closed. Thus the VTA decided to go to the main office at Vinstra, north of Vinkelfallet, while MD stayed to wait for the mechanical engineer. As he was without his car, the VTA took a lift with a truck up the valley.

Unfortunately, the main road was already closed and the truck had to return to Moksa. Arriving at 23:00, the VTA immediately realized that the situation had worsened. Water was now flowing directly towards the power station, and the excavator driver was called again. After struggling for some time with a fuel shortage for the excavator and a lack of stone blocks, they managed to gain control of the situation. The mechanical engineer then arrived. He had made a detour via small local roads to by-pass the main road between Vinkelfallet and Moksa. At 00:30 the senior engineer reported for duty, but he had had to stop by his home before he could travel to Moksa. At this point, the MD and VTA wanted to leave Moksa for the head office, but the mechanical engineer refused to stay behind alone. At 02:30, the VTA went southwards to Øyer (close to Hunderfossen, see Figure 5.2) to collect a copy of the emergency plan. On his way he caught sight of a stone quarry, which could be of great help. He reported back to Moksa that they just had to order trucks and excavators and get started!

At 03:30, the VTA made a call to the Safety Director at NVE and informed him about the situation at Vinkelfallet and Moksa. The situation at Moksa then seemed to calm down and at 03:45 MD and the VTA left Moksa, as the senior engineer had come to assist the mechanical engineer. The MD and VTA stopped at Vinkelfallet Dam and power plant on their way to Vinstra and found that the situation was under control. The water level in Vinkelfallet reservoir had decreased to 1.3 m above the spillway crest. However, the floodwater was as thick as soup with enormous amounts of debris and sediments. The roaring waterfall over the spillway crest was a horrifying sight, much like the flood of 1992 shown in Figure 5.14. They also noted that the telephone lines were down, and communication was not possible from this site. They then went home for a few hours sleep. Meanwhile the senior engineer and mechanical engineer directed the emergency works at Moksa. Additional machines and men arrived from the local road authorities. At 04:30 the mechanical engineer noticed that the riverbanks and the ground around the mill (between Moksa power plant and Moksa 1) started to behave like a quagmire. The situation was extremely critical for the mechanical engineer and one of the excavator drivers, but they managed to flee at the last minute. Shortly after, a mixture of stone, gravel, sand and water flowed towards the power plant.

The mechanical engineer rushed down to the power plant, which was still running (approximately at 04:40). They managed to stop one of the units and close the doors and gates to the powerhouse, but some water entered the building. At 05:10 the first truck with stones from the quarry arrived and the mechanical engineer ran up the hill to find a suitable place to deposit the stone blocks. He observed that a house was in danger of being taken by the river. Floodwater had broken the riverbanks immediately downstream of Moksa 1, and water was flowing in both the original and new river course. The floodwater was still eroding the banks, and the mechanical engineer decided that they should give up further attempts to stop the erosion. While busy evaluating the bank breakthrough, he suddenly realized that there might be people in the house. The mechanical engineer then asked the local authorities and rescue team to assist, and they managed to evacuate the house before damaged by the flood. At 06:00 another property was endangered, and 30 minutes later the senior engineer phoned the VTA to inform about the situation. At 09:45 on Friday 2 June, the river had eroded a new course in the alluvial fan and no water flowed via the original river channel (see Figures B-2 to B-6 and 5.20).

After the shocking "wake up" call from Moksa, the VTA went to the MGE head office at Vinstra in order to establish an emergency action group. Apart from providing information, nothing more could be done at Moksa. Meanwhile the VTA decided to secure an important transformer station at Ringebu that was in danger of inundation by Lågen River. The senior engineer, still at Moksa, called NVE to inform them of the disastrous events during the night. During the day of 2 June, MGE mostly concentrated on information and minor problems arising. In addition, they had regular inspections of Vinkelfallet Dam. Late in the evening of 2 June, a member of the Rescue Team in Øyer called to inform MGE of a possible failure of a dam on Moksa River. However, upon control at the site the observed "leakage", which had caused this alarming message, proved to be local erosion with no significance to dam safety. Unfortunately, the "failure" was already announced on the radio. The next morning, Saturday 3 June, MGE therefore had to disclaim the announced "failure".

The incorrect dam failure information was, of course, not welcomed by MGE. However, on 3 June they were happy to inform the authorities and the public that:

Figure 5.19 Attempts to protect Fonstad (left) and Moksa power plant (right) on 1 June 1995 (photo: MGE)

Figure 5.20 Moksa power plant, Stavheim mill and Moksa 1, with the new river course between Stavheim and Moksa 1 (photo: MGE)

- The situation was calm
- No lives were lost in the Moksa disaster
- Power supply had not broken down

In the following days VTA and other MGE-employees inspected the mountain storage reservoirs to look for damage to the dams and, if possible, find the causes of the event. Several theories were proposed, and literally all concerned wanted an explanation for the episode. MGE's first impression after inspection was that snow and ice in the upper part of the river basin had delayed runoff. After more thorough assessments by a geologist (Rohde 1995) and a dam safety expert (Tjugen 1995), it was concluded that the event was a natural disaster caused by extraordinarily high floodwaters eroding the riverbed and banks and cutting into the alluvial fan. The reservoirs in the mountain had delayed the runoff. However, snow and ice in the river basin had caused runoff to pulsate; indeed, several people observed "flood waves" in the Moksa River during the event. The peak discharge in Moksa River at the old power plant Moksa 1 (where breakthrough occurred) was estimated at 93 m^3/s. The corresponding peak discharge at the intake reservoir further upstream was 82.5 m^3/s (Q_{design} = 95 m^3/s). The effect of the reservoirs was an approximately 25m^3/s reduction of peak discharge at Moksa 1.Work undertaken on the alluvial fan and the riverbanks associated with the new Moksa power plant had in fact delayed the river breakthrough rather than accelerating it. In other words, even without the hydropower development in Moksa River, settlements on the alluvial fan would have been affected. The river flowing through the alluvial fan would sooner or later have changed its course due to the inherent instability in the alluvial deposits (when subjected to severe floods)! In the case of 1995, floodwater managed to move large boulders from the riverbed puncturing the natural armoring layer. Subsequently water infiltrated and eroded the finer sediments of the alluvial fan.

The event at Moksa during the 1995 flood is a useful reminder of how difficult it is to come up with possible scenarios when developing emergency action plans. Even though MGE seemingly were aware of the potential for erosion upstream of Moksa power plant, they had not expected a complete breakthrough of the riverbed and riverbanks and the subsequent development of a new river course (Skarstad 2001). Aside from other comments related to the natural disaster at Moksa, the VTA's own report of the 1995 flood (Skarstad 1995) includes the following points:

- The stage gauge at Vinkelfallet Dam should be extended and the rating curve revised
- Peak flood marks should be registered

- The emergency action plan should have been implemented at an earlier stage and the emergency relief actions should have been directed from the head office at Vinstra. It was difficult to work efficiently out in the field, especially at night and with only a mobile phone for communication.
- Although the MGE head office at Vinstra had been instructed to put the emergency action plan into effect by a fax sent at 12:20, 1 June, from the regional power company (Oppland Energiverk) the message did not reach the VTA until 6 June! There was no marking to draw attention to the extremely important contents of the message, and this may have been the reason why it was not forwarded to the VTA.

It is also worth noting that some key personnel (e.g., the mechanical engineer) worked more or less constantly over extraordinarily long shifts to solve problems at various sites. The VTA even found personnel guarding Vinkelfallet Dam who refused to go home and had to force them to take breaks. Depending on personal character and strength, working such long shifts may be acceptable for a while, but sooner or later everybody needs rest and food. These basic needs must be met by having back-up personnel, especially in the case of long lasting emergencies.

5.9.5 The failure of Tippskaret Dam, Søkkunda River

Tippskaret Dam was a small wooden dam, approximately 3 m high, at the outlet of the reservoir Myklebysjøen, which provided storage of water for Storfallet power plant (Figure 5.2). The foundations were in soil deposits and the dam was partly filled with moraine material on the upstream face, and stabilizing stones were placed on the downstream pillars (Libæk 1995). In 1987, the design outflow flood from Myklebysjøen was estimated to be 16 m^3/s. On 11 June 1995, nine days after the flood peak in this part of the river basin, the owner of Tippskaret Dam was informed about turbid water in the Søkkunda River (Kiær 1995). A local employee was asked to organize helicopter-transport to the dam site to observe what was going on. It was not possible to travel by car due to snow and melt-water along the access road. While waiting for the helicopter, the employee organized for local roads crossing Søkkunda River to be closed and a guard at the highway bridge further downstream.

After securing the roads, the local police were informed. Communication between the helicopter, police and guard was by mobile phones. Upon arrival at Tippskaret, the employee reported that the dam had failed possibly releasing three million m^3 of reservoir water into Søkkunda River and, further downstream, Glomma. The water flowing from the failed dam was clear and an old dam was observed upstream from it (in the reservoir). This second dam was holding back some of the impounded water, and the observers decided it was safe, despite being overtopped by 20-30 cm. The area between Myklebysjøen and the confluence with Glomma was controlled from the helicopter, and as no serious damage was observed the helicopter returned to its base. Road closures and regular controls of the highway bridge were kept until the next day.

This dam failure caused no serious damage. The only sign of failure at the confluence with Glomma was, in fact, increased turbidity in Søkkunda River. The fact that the dam failed several days after the flood peak was explained as follows by the investigating consultant (Libæk 1995): "*The flood discharge between 28 May and 3 June over the dam may have triggered erosion of the northern abutment. In connection with the increased discharge between 8 and 11 June this may have caused severe erosion and failure of the dam foundation.*" The flood peak from Myklebysjøen is not known but registrations at Storfallet power plant show a maximum of 61.4 m^3/s on 2 June and 52 m^3/s on 11 June (Kiær 1995), indicating that the discharge over Tippskaret Dam was larger on 2 June than when the dam failed.

The dam owner had not established a formal emergency plan before this event, but he had participated in an emergency handling course and a dam safety course. He felt that he, as owner and VTA and with the assistance of skilled employees, had handled the situation fairly well. He also pointed out the benefit of his experience as an Army officer. This supports the author's opinion of the importance of experience and training regarding the handling of emergencies. Another comment regarding this incident is that nothing in the reports indicates that the dam was inspected between the flood peak and the day of the dam failure. An inspection may have revealed damage to the dam foundation after the flood peak, and perhaps triggered immediate actions to prevent further damage.

5.9.6 Lessons learnt from the 1995 flood

There was a distinct difference in the way in which the flood affected large run-of-river power plants and dams in the main rivers as opposed to smaller developments in the steeper tributaries. The severity of the flood in 1995 could indicate that many dams and power plants in the main rivers would experience major problems. However, due to the reasonably early detection of the developing flood and the time delay from the headwaters of the catchment to the large dams in the lower reaches, there was time to make necessary preparations for diversion of the large flood volume at the dams in the main rivers. At several dams, discharges above the capacity of the spillways were expected and provisional arrangements were made to increase their capacity and protect valuable power plant installations (see Figures 5.16 and B-10). There was also a general desire to keep the power plants in operation thereby increasing the total discharge capacity. Most measures proved successful.

The tributaries to the west of Glomma and to the east of Lågen, north of Elverum/Lillehammer, were characterized by rapid development of the flood. The failure of Tippskaret Dam and the natural disaster at Moksa both occurred within this region. The situation was also critical at Vinkelfallet Dam in Våla River, but no damage occurred. However, the peak water level was extremely high at Vinkelfallet Dam, and observed flood peak was probably 200 m^3/s, which is 80 % of the design flood (Grøttå 1995). Enormous amounts of debris passed the spillway during the flood, as described above. Signs of landslides and large debris were also observed in the reservoir upon inspection after the flood by MGE and the author (see Appendix B), but fortunately, the dam had recently been modified to allow passage of debris as described earlier. The flood impact on roads in the valley of Gudbrandsdalen was extensive, in many places due to erosion and scouring from the tributaries to Lågen, as described by Lind et al. (1995). Road blockages caused problems for MGE, having facilities located at several places in the valley from Vinstra in the north to Øyer in the south. In other areas, substantial problems also occurred due to damage to, and overtopping of, flood dikes/levees. This was one of the main concerns for local authorities and the public (see for example Hagen 1995; Skullerud 1995). An evaluation of flood handling with emphasis on securing levees along Glomma has been performed (Krasovskaia et al. 2000). Some of the conclusions made can be transferred to emergency operations at dams, such as the benefit of using local media to release flood information (see also below).

Many of the dam owners expressed the benefit of having emergency action plans and/or emergency training with respect to their ability to cope with the flood. Emergency action groups were established in several companies, but several commented that the messages containing flood warnings and calls for emergency action groups from the authorities had been anonymous. In some cases, this resulted in a lack of response to the developing emergency. One VTA even reported that the "second in command" in his company had left for a holiday on 1 June. In contrast, another reported that all employees of his organization were informed on 18 May of an exception to the Working Environment Act, which required that they did not take time from work during the upcoming flood. Some of the people involved in emergency mitigation were overloaded with work and responsibility. The need for qualified relief personnel was obvious in some cases. At many dams "flood tourists" caused unnecessary extra strain on dam and power plant personnel. The army, the civil defense and the police gave valuable assistance as guards and securing facilities against inundation.

Media interest was rather overwhelming, but while some events where highly publicized, others, such as the pre-release of water from many dams in the lower part of Glomma River, were hardly mentioned. Similarly, the disastrous breakthrough of Moksa River at Tretten made front-page news, while the dam failure at Myklebysjøen literally drowned under the weight of other interesting incidents. The contrast was probably because the former incident affected people and property heavily. For some dam owners, media pressure was an extra burden during the difficult situation, but one felt that media was not interested enough in them! There was also a distinct difference between local media and national media. Local radio stations actively assisted dam owners, local authorities and others in giving timely and valuable information, while national TV-companies and newspapers often focused narrowly on what (they believed) were the big sensations. Many reports from national media also demonstrated that the journalists had little understanding of floods and flood handling.

5.9.7 The follow-up of the 1995 flood

Directly after the flood, on 13 July 1995, The Commission on Flood Protection Measures was established by Royal decree. The Commission dealt with measures for reducing the vulnerability of society to floods and flooding (NED 2000). Some of their many recommendations were to use risk analyses and flood zone mapping to assess vulnerability to flooding and thereby provide a basis for land use planning and planning of flood mitigation measures. Flood zone mapping is currently undertaken by NVE for the most vulnerable areas, and several maps have been issued already. Extra focus was placed on Lake Øyeren and Solbergfoss Dam to provide better and safer discharge capacity and subsequent lowering of flood water levels in Øyeren. The best solution for Øyeren was the installation of a new spillway gate as shown in Figure 5.24. The Commission also gave some recommendations to the research program HYDRA, which was initiated prior to the flood. The objective of HYDRA was to assess whether land use changes and other physical measures had led to an increased risk of floods (Eikenæs et al. 2000). The project was not directed towards problems related to power plants and dams but rather towards local communities, the public and the environment. The results are presented in 24 reports covering the following topics:

- Flood mitigation, flood protection and flood handling
- Environmental effects of flood and flood prevention measures
- Nature and land use
- Risk analysis
- Densely populated areas

Some of the reports are of interest also for this study and have been referred to where relevant.

5.10 The 1996 flood in the Saguenay region, Québec, Canada

From 18 to 20 July 1996, an area of more than 210 000 km^2 in southern Québec was affected by torrential rain. Most damage occurred in the largest river basin of the Saguenay River and Lake Saint Jean with an area of 106 000 km^2. The river basin has about 40 significant rivers and many lakes including more than 2000 dams and dykes. At Kénogami Reservoir, which was most affected, the 10 000-year flood was estimated to be 1500 m^3/s in 1988 (Tawil 1998). This flood was exceeded by 850 m^3/s. In other words, the 1996 peak flood was approximately 2350 m^3/s. The maximum daily inflow to Kénogami Reservoir was more than twice the greatest inflow during the 80 years observation period. The damage caused by the rapidly increasing flood was extensive and included:

- Erosion of river banks, deepening of channels and rivers taking new courses
- Overtopping or failure of dams and dykes (including failure of the 21-meter high Kénogami earth dam)
- Disruption of power supply, damage or malfunction of hydropower plants and hydraulic components
- Collapse of roads, bridges and railroads
- Extensive damage to private property, commercial facilities and municipal infrastructure including disrupted access to essential services

Directly after the flood, the Canadian government instituted a "Scientific and Technical Committee on the Management of Dams". The committee found, among others, that the affected population was largely unaware of the hazards. Regional and local authorities had not been able to fulfill their responsibility for public safety. In addition, many owners and operators of dams and hydropower plants either did not have complete and updated emergency plans or did not take full responsibility for their structures. The committee therefore produced many recommendations to improve management of severe floods in the future:

- Revision of Québec Water Courses Act
- Establishment of an Authority Responsible for Safety of Dams
- Prepare a register of dams
- Establish public watershed committees for all rivers with hydraulic facilities
- Develop new criteria and policies for flood plain management corresponding to 20- and 100-year floods

The performance of gated spillways during the 1996 Saguenay flood has been investigated by Léger et al. (2000). It appears that most of the affected dams experienced malfunctions due to disrupted power supply or jammed stop logs. High water levels (due to slow reaction to the impending flood) forced many dam operators to abandon manual lifting operations. Other problems reported were inadequate access to the gates, lack of key personnel, failure of hoists and insufficient spillway capacity. Insufficient spillway capacity resulted in failure of riverbanks at several sites, allowing the flood to bypass the dam. The floating debris produced by the flood included wood logs, trees, boats, cars, cottages and household furniture. Floating debris not only reduced spillway capacity but also produced significant loads on the hydraulic structures during the flood.

As mentioned above, the committee recommended establishment of watershed committees with one of the main responsibilities being the coordination of gate operation at various dams with different owners (analogous to GLB's function during floods in Norway). However, there was also a need to increase spillway capacities, and to evaluate the apparent incoherence between large spillway capacities upstream and low spillway capacities at downstream dams. The committee gave the following specific recommendations to improve the performance of gated spillways (Léger et al. 2000):

- The spillway capacity of existing dams should be reviewed
- All spillway discharge control systems using wooden stop logs should be eliminated
- Auxiliary power supply should be installed in an area protected from floodwaters
- The design and operation of spillways should consider floating debris
- Access to spillways should be available at all times, i.e. alternative roads and helicopter pads must be planned for remote sites

Other recommendations included new risk-based methods for determination of required spillway capacity and new methods for assessment of overtopping of concrete dams. The behavior of spillways and dams during the Saguenay flood illuminates problems that have been previously experienced world wide according to Léger et al. The other cases presented above underline this statement. The use of stop logs in spillways, for example, was recognized as inadequate after the failure of Noppikoski Dam in 1985 and once more after the 1987 flood in Norway. The Saguenay flood is a good reminder of the importance of all the safety measures already implemented or emphasized in Norway.

5.11 The 1997 flood in Stora Göljån River, Fulufjället, Sweden

The most intense rainstorm ever documented in Sweden occurred at Mount Fulufjället on the Norwegian border on 30 - 31 August 1997 (Vedin et al. 1999). The resulting flash flood caused extensive damage in the small tributaries to the Fulan River east of Fulufjället. The mean discharge for August in Fulan River, observed approximately 30-40 km downstream of where the Stora- and Lilla Göljån rivers join Fulan, is 17 m^3/s. In the night of 30 August 1997, a peak discharge of 317 m^3/s was observed for the Fulan River (Alexandersson et al. 1997), Figure 5.21. The observed discharge was later found to be approximately 10% too high due to changes to the cross-section at the gauging station during the flood (Vedin et al. 1999). Vedin et al. give a detailed description of the weather situation, probable 24-hour precipitation, and observed and estimated peak discharges. The maximum 24-hour precipitation is estimated to have been 300 - 400 mm in the upper parts of Stora Göljån, along the eastern ridge of Fulufjället. The estimated peak discharge at the new common outlet of the Stora- and Lilla Göljån rivers on 31 August 1997 was 300 m^3/s, while mean annual discharge is approximately 1 m^3/s. In addition to the heavy rainfall that caused this flood, there was also extensive lightning activity.

Dan Lundquist, GLB and the author observed the effects of the flash flood during a field trip in 1999 (see Appendix C). Detailed descriptions of the geomorphic effects in the area are given by Borgström et al. (1999). The most affected area was within the catchment of Stora Göljån River, which also happens to be a nature conservation area. In other words, evidence of the 1997 flash flood will be preserved for the future, just like the Lawn Lake dam failure described in Section 2.3.4. The following features should be noted from the flash flood in Stora Göljån:

- Erosion caused extensive widening of the river channels, mass movement and removal of vegetation
- Approximately 10 000 uprooted trees were deposited upstream of two culverts at the forest road upstream of the confluence with Fulan
- Boulders more than 1 m^3 in size were transported by Stora Göljån
- Trees were under one meter sediment deposits
- The increase in discharge was rapid leaving little time for warning to be given
- The return period for the rainstorm has been estimated to be 10 000 years for a specific 1000 km^2 area in the Fulufjället region

Alexandersson et al. (1997) comment that this event could have occurred in an area with more developments, indicating that the event obviously has relevance to dam safety.

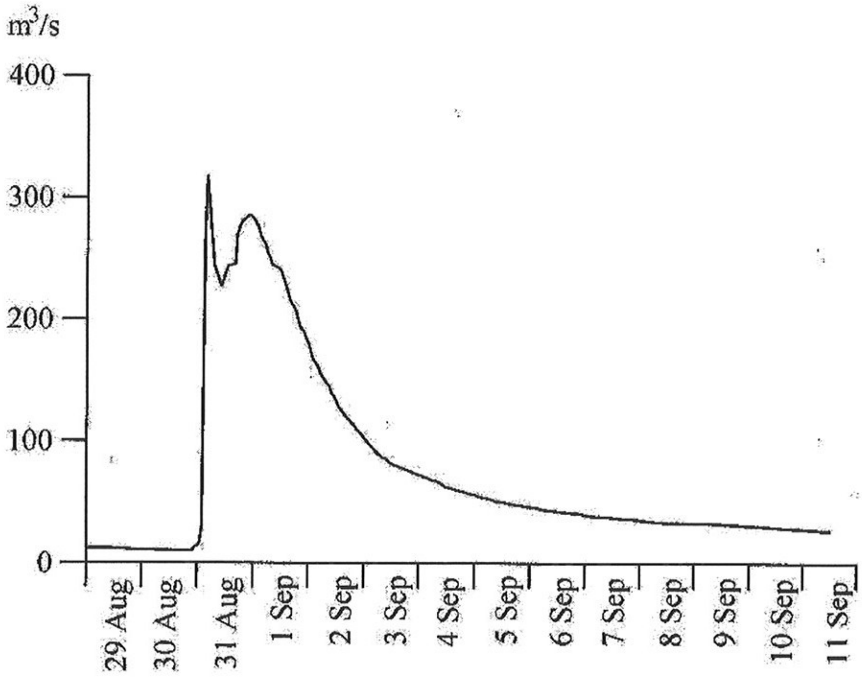


Figure 5.21 Discharge at Fulunäs, Fulan River (catchment area = 882 km^2)

5.12 The 2000 flood in lower and middle Glomma River Basin

Extreme precipitation and unusually high temperatures during the months of October – December 2000 caused a flood with long duration in the lower and middle reaches of Glomma River Basin. Several small river basins in the Oslo area was also seriously affected, such as the Hobølelva and Akerselva river basins, and inundation of usually dry areas was a common sight during the autumn of 2000 (Figures 5.22 and 5.23). Precipitation was the greatest recorded at several locations in November. The affected area was limited by Vinstra River to the northwest and Osen catchment to the northeast (GLB 2001). In the northern catchments of Glomma River Basin there was unusually low precipitation in the same period.

5.12.1 Glomma River

The flood in the Glomma River upstream of the confluence with Vorma River (Lågen River Basin) was fairly moderate. Lake Øyeren, however, experienced a long lasting flood with peak water level 0.89 m above HRWL on 22 November. Prior to the flood peak and with special permission from NVE, GLB released up to 200 m^3/s water more than the operational rules allow. This was done to reduce damage around Lake Øyeren. Mean discharge from Lake Øyeren from 1 October to 15 December was 1 520 m^3/s representing approximately 10 000 million m^3, or almost 50 % of the annual runoff. The instantaneous peak discharge from Solbergfoss Dam and power plant (Figure 5.24) reached 2200 m^3/s on 22 November, the highest recorded peak ever observed during this time of the year.

5.12.2 Vinstra River

Precipitation at Bygdin was 291 mm for October and 210 mm for November (normal values are 112 mm and 86 mm respectively). Most of the precipitation in October was rain due to temperatures above normal. Total inflow to Olstappen Reservoir on the Vinstra River during October was 208 million m^3, which was the highest observed monthly inflow during the observation period 1908-2000 and is three times the average monthly inflow for that period. Despite this unusually high inflow, there were no floods in Vinstra River as GLB actively used the reservoirs and power plants to avoid flooding in the river reaches.

Figure 5.22 Some impressions from the usually small River Hobølelva, 18 November 2000

Figure 5.23 River Akerselva at Frysja, Oslo, November 2000 - photos taken with a few days intervals (photo: L.B. Lian)

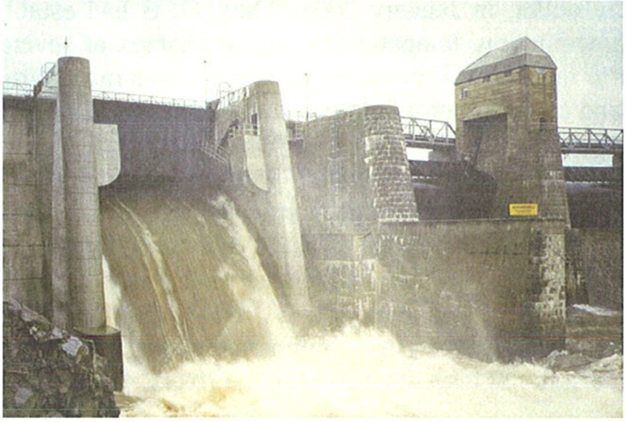


Figure 5.24 Solbergfoss Dam with new spillway gate on 18 November 2000

5.12.3 Lake Hurdalsjøen and River Andelva

The Hurdal region was probably the most heavily affected area in Glomma River Basin during the 2000 flood, and received 815 mm precipitation during October and November. Lake Hurdalssjøen (Figure 5.2) reached an historic level of 178.1 m asl on 25 November – 1.8 m above HRWL (Lundquist 2000). The flood was estimated to have had a return period of 50 years or less for a duration less than two weeks or approximately 1 000 years for a duration of two months (Lundquist 2001a). The estimated return period for the peak water level was 200 years. Lundquist also pointed out the problem with estimation of 1000-year floods (design floods) in lakes with narrow outlets, due to the long duration periods possible and consequently the possibility of multi-peak floods.

The record high water level in Hurdalssjøen caused some inundation of roads and bridges around the lake. Most damage was caused along the downstream River Andelva. There were some concerns about possible slides in clay deposits along the river as the rain continued to fall. Four out of five power plants were put out of operation and several companies had to consider temporary redundancies. A particularly dramatic event occurred on the evening of 21 November when the power plant Mago C had a sudden shutdown due to power failure. The training wall upstream the power plant was soon overtopped and the power plant was completely flooded in a short time. The operation manager was barely able to escape, being trapped inside the powerhouse by the floodwaters.

GLB was scheduled to take over the responsibility of Hurdalssjøen, including the dam at the outlet, in January 2001. Thus, GLB had established gauging stations for precipitation, temperatures and discharges at several locations in the area prior to the flood. They managed to develop a rainfall/runoff model by 6 November and could therefore prepare flood forecasts in order to evaluate the need for emergency measures. GLB assisted the operators from the power company during the most critical period with operation of stop log spillways. In addition, GLB took care of information to the media and others, partly because they were directly asked to assist and partly because the operating company did not recognize the need for an emergency alert. Apart from the incident at Mago C power plant on 21 November, no critical situations occurred in the river system. There were some slides, but they were triggered by the saturated soil, not high discharges in the rivers.

5.13 Discussion

The cases presented here are the result of a literature study, interviews and observations made by the author. The criteria mentioned in Section 5.1 have governed case selection. There were several cases possibly of interest that were not investigated further, such as the flood in Etne River, which peaked at 250 m^3/s (2000 l/sec·km). This flood, with an estimated return period of 2 000 years, resulted from record rainfall in November 1940; 230 mm in 24 hours or 379 mm in 48 hours (Beldring et al. 1989). The flood in Gaula in 1940 is another interesting event. The peak discharge for the 3500 km^2 catchment area reached 3000 m^3/s (Eikenæs et.al. 2000). For creation of a flood scenario in Vinstra River, however, the cases presented are considered to be sufficient.

Very few have experienced true extreme floods, and examples from regulated rivers are rare. It was therefore found interesting to include the cases from River Jostedøla and Fulufjället. It should be noted that these extreme floods occurred in steep river basins, causing damage specific to those conditions. Jostedøla River Basin is also dominated by glacier runoff, which contributed heavily to the magnitude of the described floods in 1898 and 1979.

Several cases demonstrate that there is a tendency for problems to pile up during a flood, such as was the case for Lutufallet. As a consequence, theoretically manageable floods can easily develop into a critical situation. Furthermore, it is worth noting that risk analyses cannot guarantee identification of all possible failure scenarios, as was demonstrated at Braskereidfoss, which was affected by the 1987 flood. In general, it should be noted that deviations from the typical flood pattern may occur, which should be accounted for in future dam safety analyses (see also discussion on climate changes in Chapter 2). The long duration of the autumn flood of 2000 in Glomma River Basin is a typical example. The characteristics of different floods with respect to duration and geographical extent will influence, among others, flood warning (i.e. warnings that put emergency action plans into effect) and access to adequate resources (see below). Several of the critical situations described here occurred directly prior to or during weekends or holidays, which also should be accounted for in future analyses. At Noppikoski and Lutufallet the dam owners experienced problems in getting adequate resources due to the timing of the flood.

Even though cases from countries other than Norway have not been prioritized, it has been recognized that there is much valuable information available, especially from the operation of dams during floods. Interesting references have been found in proceedings from various conferences dealing with extreme floods or dam operations or both. One example is Alexander and Kovács (1988) who dealt with dam operation during exceptional floods in Southern Africa at the ICOLD 16th Congress in San Fransisco in 1988. Their paper confirms some of the problems found in the cases presented here such as disrupted telecommunication. Alexander and Kovács also point out the importance of the time aspect in the operation of spillway gates during floods. Thus, ensuring sufficient discharge capacity is not enough when spillway gates are provided in a dam. The designer must also evaluate the time needed for assessing the magnitude of the incoming flood and subsequently the time required for taking action including opening gates. This time must not exceed the rate of water level rise in the reservoir.

In Norway, many dams are located far away from control centers and operation of gates relies on remote monitoring and acquisition of data. These systems will most probably not function during a severe flood. Dams will have to be operated and monitored on site. Local operation necessitates instructions for timely relocation of dam operators taking into account the possibility of poor access. Communication systems must be expected to be out of order and the dam operators may have to operate alone. Skilled dam operators will be a prerequisite in such a situation. Simple written operation procedures, as suggested in a paper to the ICOLD Congress in Beijing (Pyke an Grant 2000), should be prepared to achieve the best possible result from local operation. The suggested operation rules are based on water level registrations and the settings of the outlet openings. It should be noted that the use of these simple operation rules is restricted to reservoirs where water levels are allowed to rise above normal operation levels.

Some of the cases presented here, along with other publications, underline the vulnerability of gated spillways due to the need for an external power supply or manual power in situations when access roads, power lines and so on are highly unreliable. The need for establishing emergency procedures to be followed in cases of severe floods is obvious. Many of the technical aspects of dam operation during floods are gradually becoming common knowledge among dam safety experts. However, in addition to improving their own knowledge as technical systems change, the experts of today should be aware of the importance of transferring their knowledge to new generations. During the 1995 flood, for example, experience and competence of dams, floods and emergency management proved to be very valuable for many dam owners. The value of having experienced and competent dam operators was also recognized in the 1987-flood. Indeed, one of the larger dam owners pointed out that local dam operators with experience from manual dam operation had been of vital importance. Furthermore, the need for qualified substitutes for all key functions during an emergency should be noted, especially when the emergency is extensive and long lasting. Care must be taken to avoid resource conflict, when qualified personnel or adequate material are scarce. For instance, several dam owners may have counted on using the same external resources. Such problems should be eliminated by coordination of emergency action plans, and by ensuring a minimum level of resources held by the dam owner. Attention should also be paid to the behavior of the media, as journalists are actively hunting sensational headlines and scapegoats more than ever before. This can cause extra strain on key personnel and distract from important emergency actions if the media is not accounted for in the emergency plan.

The importance of the "human factor" during a severe flood deserves more attention as recognized by, for example, Lempérière (1999) and Rissler (2001). Many of the problems encountered during floods could have been avoided if the human factor had been emphasized more. Lempérière points out the need for increased interest in this subject. Rissler also discusses how studies of human reliability from other fields, such as nuclear power plants, can be utilized. However, the relevance to dam safety seems to be restricted to operation centers. The differences in "emergency and system characteristics" between accidents at nuclear power plants and handling extreme floods must be taken into consideration. Some comments on administrative matters during emergencies, as well as the psychological aspects of human response to emergencies have been given above. These matters are beyond the scope of this thesis, but there is obviously a need for study and discussion elsewhere.

5.14 Conclusion

It is hoped that the cases presented here can be used as a knowledge base for emergency exercises or analyses of dam safety. However, where used it will be important to evaluate the relevance of each case with respect to flood event and technical and administrative systems. Most of the findings are probably not surprising, but hopefully they can serve as a reminder of the extent and complexity of floods, and the importance of emergency action planning.

6 CREATION OF FLOOD SCENARIOS

6.1 Introduction

Scenarios are typically used as a “tool for foresight” when information about the future is lacking. In business, scenario based planning has been used since the early 1960s (Geus 1997). According to Geus, Herman Kahn, a well-known futurist, coined this usage of "scenario" taking it from the movie industry. According to the Oxford Dictionary (Pearsall 2001), a scenario can be defined as:

1. *A written outline of a film, novel, or stage work giving details of the plot and individual scenes*
2. *A postulated sequence or development of events*

The term scenario is presently used in many different contexts for analyses and planning such as business administration and climate research. In the context of dam safety, scenarios are used as basis for analyses or emergency exercises. Flood scenarios, which are the main focus of this thesis, are naturally associated with various secondary effects, or events, some of which pose a potential threat to dam safety. Some examples of the use of scenarios from the oil and hydropower industry are given below along with recommendations for and a discussion of the creation and use of flood scenarios.

6.2 Some experiences from previous use of scenarios

6.2.1 The oil industry

The planning division of Dutch Shell developed a technique for using scenarios founded on the ideas of Kahn (Geus 1997). The scenario planning in Shell was based on key questions such as:

- How do we look 20 to 30 years ahead?
- How can we get people to discuss the "unthinkable"?

In practice, the scenario writers worked a year or two assembling data and then presented their anticipation of the future in a story of approximately 70 pages. The Shell Committee of Managing Directors (CMD) approved the scenario writers and the set of scenarios before they were presented to the Shell community. The CMD's practice of approving the integrity and sound judgment of the principal scenario writers was important for further approval of scenarios within Shell, especially in cases where the scenarios seemed improbable. The "Shell method" was to work with scenarios, which were relevant for their business (the oil industry), and which helped the managers to see the relevance of global forces and possible futures.

Another utilization of scenarios was developed at SINTEF (Ingstad and Bodsberg 1990). Developments made in the CRIOP-project (Crisis Intervention in Offshore Production) resulted in a scenario-method for evaluating offshore control rooms. The CRIOP-method is based on scenarios derived from real accidents at the installation in question or other installations or hypothetical accidents (from risk assessments). The main elements of the CRIOP-method are:

- General Analysis
- Scenario Analysis

The General Analysis is in short an analysis based on checklists or simple qualitative methods to identify problems in the control room (offshore), with emphasis on the working environment of the operators. This analysis is conducted "once and for all" and serves as a static assessment of control room design and functions. The Scenario Analysis, however, focuses on control room actions in response to possible accidents scenarios. It should be founded on the preceding General Analysis. The steps of the Scenario Analysis are:

- Choose scenario
- Adapt scenario to local conditions
- Graphic presentation of events (using STEP-method)
- Identification of problems in accomplishing tasks/handling situation
- Recommend improvements

The typical scenario used in the scenario analysis is of relatively short duration (minutes/hours), has a defined and limited number of actors and emphasizes components in a closed system with limited geographical extent. The scenario is presented in a well-arranged and logical way by means of the established STEP-method (Sequentially Timed Events Plotting). The STEP-method emphasizes actions by different actors and links between actions. The STEP-diagrams are simple to follow (Figure 6.1). Focus is put on the operator actions during development of the STEP-diagram. The subsequent identification of weak points in operator's handling of the scenario is based on a scenario checklist. Finally, recommendations for improved handling of the scenario are given, which are based on the findings of the analysis. Experiences from the CRIOP-project indicate that personnel participating in the design of scenarios and in the subsequent analysis increase their awareness of handling abnormal situations. In other words, there is a positive pedagogical effect inherent in this analysis method. Ingstad and Bodsberg also conclude that simplified scenario sessions may serve as a retraining method for control room operators.

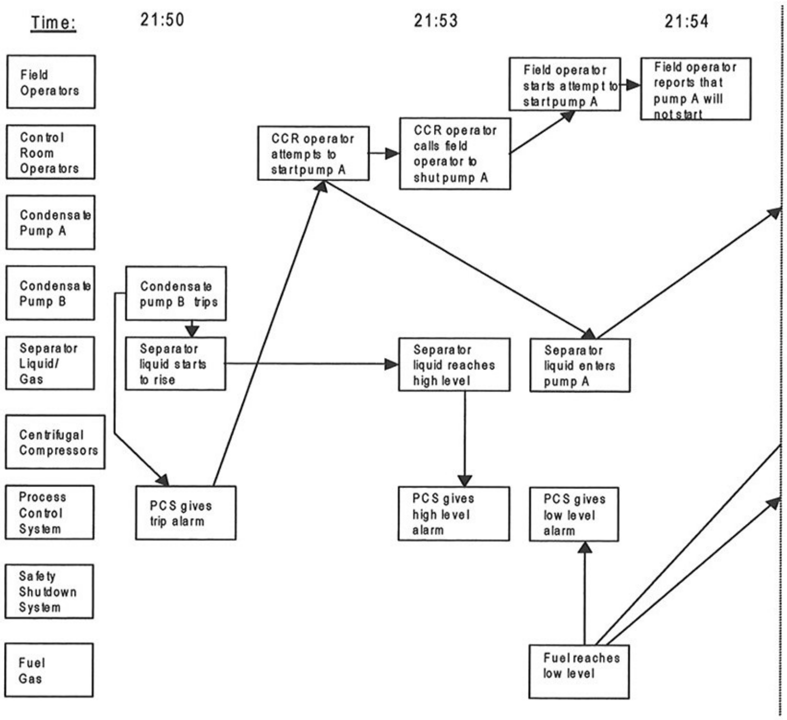


Figure 6.1 Extract of STEP-diagram from the CRIOP-project

6.2.2 The hydropower industry

Scenarios are mostly used for production planning, risk assessments and emergency planning and exercises. In the risk analysis context where each dam is analyzed separately, scenarios may be in the form of failure sequences broken down into component events (see for example Johansen et al. 1997). Event trees are suitable for analysis and presentation of possible failure sequences at single dams. In Norway, functional emergency exercises (see Section 4.6.2) are based on scenarios presented as a script. The scenarios are mostly developed within the dam owner organization, or by an external consultant working in cooperation with selected personnel. The scenario writer often uses a mixture of personal experience, knowledge of typical emergency situations and sheer imagination. For dam emergency exercises, the scenarios are typically based on a severe flood event, while an explosion or fire or both within an underground powerhouse is a typical base event for power plant emergency exercises. Some scenarios are also designed as exercises for both power plant and dam personnel, that is, they include simultaneous severe problems at power plants and dams. Focus is often put on the secondary effects of the base event and interruptive messages from media and stakeholders in the river basin. As floods normally occur in a whole river basin simultaneously, emergency scenarios also may focus on several dams within a basin. A script prepared for functional (role-play) exercises contain many messages arranged in a time series, some times with an "open end" with room left for improvisations from the exercise organizers at the end of the exercise. The exercise simulation staff, which sends messages to the participants according to the written script, is usually located within a separate room with telephone contact to the participants.

6.3 Design of flood scenarios for dam emergency exercises

6.3.1 Method overview

A systematic way of creating scenarios for dam emergency exercises, which are presented as scripts in the functional exercises, has not been found. Therefore a method for creation of flood scenarios for functional emergency exercises is presented in this section. Comments are also given as to how the scenarios can be adapted to use in RIFA. The method given here is based on ideas from the CRIOP-project (Ingstad and Bodsberg 1990). Flood scenarios can be based on recent floods, either in the actual river system or in a similar river system, simulated historical floods or hypothetical floods. Even though a scenario is basically hypothetic, as it presents a possible sequence or development of events, the credibility of the scenario will naturally increase by using real events as a basis. Real floods should therefore be emphasized in order to gain acceptance among those being subjected to the scenario (i.e. participants in exercises or analyses). Using real floods as basis does not exclude the use of additional imaginative and "improbable" events in the scenario.

Experiences from recent floods in rivers, emergency exercises and discussions within the RIFA-project indicate that there are some main features that should be included in every exercise scenario:

- Messages and inquiries, sometimes highly irrelevant to the situation, from stakeholders, local community and others
- Constant pressure from media looking for front page-stories
- Unexpected problems with technical equipment
- Indistinct responsibilities

In addition, there are some features, commonly experienced, that can be included in a scenario to increase the stress on the participants, such as:

- Accidents, injuries or even fatalities among personnel or others with some kind of relation to the situation
- "Disaster-tourists", especially in urban areas
- Communication problems due to extraordinary loading on telecommunication systems or weather conditions

"Improbable" events should also be considered as part of an exercise in order to put extra strain on the participants.

In general, the flood scenario should comprise (see further description below):

1. A flood event (characterized by its inflow hydrograph)
2. Prevailing weather conditions
3. Natural hazards associated with the flood
4. Secondary effects of the flood and natural hazards
5. Operational and administrative problems
6. External disturbances (such as inquiries from media and stakeholders)

The initial conditions of some of the items listed above will be specified prior to the exercise as information to the participants. Further development of the flood scenario will be introduced to the players as the exercise proceeds. Item 5 includes predefined problems, while additional operational and administrative problems may appear during the exercise, as a result of how well the participants are able to handle the flood scenario. For simulation with RIFA, a pool of resources must be specified as part of the starting conditions for the scenario (Alfredsen et al. 2001). The duration of the flood scenario must be long enough to include any significant problems caused by the flood. Likewise, the time intervals must be adjusted to the duration of the exercise and the basis flood event. It is normally adequate to use a compressed time-scale during the exercise. RIFA also allows a user-controlled time-step.

Preparations

Before starting the process of creating a flood scenario, a visit to the river system is recommended. The visit should include as much as possible of the technical system and the surroundings. Separate interviews or informal meetings with local dam operators are also recommended, as they can hold information about operational problems not necessarily known to others. The scenario-writer will, in general, benefit from having close contact with key personnel within the dam owner organization. The present state of the actual dams and related administrative systems should be known and documented. Such documentation will facilitate the process of developing a flood scenario, by indicating vulnerable parts of a dam system and the administrative systems. Relevant documentation includes the features of the dams and appurtenant catchments, critical limits for reservoir water levels and discharges, operation procedures and available resources, that is the documentation which is supposed to be available as part of the emergency action plans. Results from previous safety inspections and assessments should also be included. The system documentation is essential in the process of assessing secondary effects of the flood and other problems to be added to the flood scenario.

Selection of basic flood

The starting point for creation of a flood scenario is selection of the basic flood event. The basic flood may be an extreme flood of the same magnitude or greater than the design flood. However, it is often found more relevant to use a more moderate flood, for example a major flood combined with other events that may threaten the overall dam safety. The most interesting floods for establishing of scenarios are usually those that have caused damage and operational problems at dams. Due to their rare occurrence, many existing dams have not yet been subjected to such floods. Therefore, historical floods or floods from comparable catchments or both may be found to be relevant to use as a basis for the scenario. Recent floods are normally well documented with extensive data records, possibly also including relevant information about operational problems. Historical floods, on the other hand are floods preceding the gauged period of record, see Section 2.2.2. Even though official registrations of water levels and discharges may be missing, other data from historical floods may be utilized such as registration of maximum water levels and descriptions of duration, weather conditions and secondary effects. Pure hypothetical floods, such as the theoretical design flood or PMF for a dam can also be used as the basic event. If so, weather conditions, natural accidents and secondary effects have to be added to the event by using knowledge gained from real floods combined with expert judgment. Experiences from extreme floods are, of course, of special relevance in this context.

In summary, the following sources of scenarios are recognized:

- Recent floods in the actual river system
- Historical floods in the actual river system
- Recent floods in a comparable river system
- Historical floods in a comparable river system
- Hypothetical floods (for example the design flood)

When there is a lack of data for an interesting flood, it may be relevant to combine several similar floods in order to create a complete scenario. Criteria for selection of scenarios may vary from case to case, depending on the purpose of the emergency exercise. Most importantly the scenario must be physically possible in the river system in question. The scenario must furthermore have the potential for causing major accidents or severe operational problems at the dams in question.

Simulation of the basic flood

The flood should be described by its inflow hydrographs to the river system. For recent floods there will normally be enough data available for simulation of inflows by rainfall-runoff models. Flood propagation throughout the river system, and during the exercise, can be fixed by the exercise organizer or be controlled partly by the participants, as is the case with RIFA (see Section 4.6.2). In any case, preliminary flood routing through the river system is recommended, with a specific release pattern from the reservoirs, independent of the degree of user-interaction with the flood routing during the exercise or training session. Results from the preliminary routing may indicate possible secondary effects that can be added to the scenario. For historical floods, hydrological or meteorological data or both are normally insufficient, but in some cases quantitative data can be derived from qualitative descriptions of the flood and prevailing weather conditions. Registered maximum water levels are sometimes available for control of simulation results. In cases were the selected flood scenario may theoretically lead to dam failure, a dam break analysis may also be required. When dam break analyses are not available, or when evacuation and rescue operations are excluded from the exercise, a dam failure will obviously be the end event of the exercise.

Weather conditions, natural hazards and secondary effects

The prevailing weather conditions are important for evaluation of both natural hazards (landslides, erosion, lightning strike and so on) and secondary effects (disrupted transmission lines, impassable access roads and so on). Their description is therefore an integral part of any flood scenario. For some basis floods, detailed weather descriptions, which cover the entire flood, are available. For others, experts must reconstruct the probable weather conditions associated with the basis flood. Information about natural hazards associated with the flood and possible secondary effects must be added at the time considered appropriate within the flood scenario. The natural hazards and secondary effects associated with an historical flood may need to be adjusted with respect to major changes in the catchment over time, such as new or changed infrastructure. In cases where data are transferred from river basins or dams other than those emphasized in the exercise, the need for spatial adjustments of data must be evaluated. Some secondary effects will be governed by exceedance of critical limits, which will become apparent after the initial routing of the flood through the river system (see above). Several flood-routing iterations may therefore be necessary before the flood scenario is complete.

Operational and administrative problems

Operational problems are those related directly to the operation of reservoirs, such as a spillway gate being out of operation due to damage or revision work. Administrative problems are typically a lack of personnel, usually over holidays or weekends, or deviations from the operational procedures. As mentioned above, indistinct responsibilities within the dam owner organization is a highly relevant element of emergency exercises. Operational and administrative problems may be given as starting conditions for the scenario, but in order to increase the degree of difficulty some operational and administrative problems can be introduced to the participants during the exercise. Experiences from recent floods in the actual or comparable river systems by dam owner organizations are the most relevant to build on. Results from safety analyses and anticipated developments of the technical system or within the dam owner organization may also be included in the scenario, for example work force reductions. It should be noted that valuable information on operational and administrative problems is often taken from (local) dam operators (see above).

External disturbances

External disturbances included in a flood scenario are typically inquiries from media and the public, as is mentioned above. Emphasizing the most recent experiences is most relevant due to media development. Cooperation with media representatives should be considered to increase the realism of the scenario. If journalists are part of the exercise simulation staff, they will normally be able to improvise. In RIFA, and in cases where journalists are not included in the simulation staff, media pressure must be written into the script.

Presentation of the scenario

The scenario can be in the form of a written script only where flood propagation is fixed by the scenario writer and is communicated verbally to the participants. Flood propagation is then indicated via a weather forecast, sometimes in combination with "observed" meteorological/hydrological data. Another possibility is to have a written script combined with a fictitious observation series of hydrological or meteorological data. The series are communicated to the participants as the exercise proceeds (for example as fictitious on-line computer data from dam operation centers). Scripts for functional exercises comprise only messages from the exercise simulation staff to the participants. Scripts for RIFA must also include alternative responses to each message and possible follow-up messages, while flood propagation is visualized simultaneously as hydrographs for each reservoir.

6.3.2 Sources of information

Recent severe floods are normally well documented. Thus, necessary data is normally at hand from a variety of sources. There may even be personnel or others available to supply interesting details about operational problems and other relevant information. Historic severe floods may also be known, but relevant data may be more difficult to find. In cases where no interesting floods are known, information can be found in various flood records (for example Rodier and Roche 1984; Roald 1999). When data on previous floods is not readily available, or when it is necessary to extend the information base about a particular flood, the following sources of information should be investigated:

- Earlier studies of a flood event reported in journals, conference proceedings, reports and so on
- Data from hydrological and/or meteorological records
- Documents held in local, district or regional libraries
- Local history books
- Newspaper articles
- Oral descriptions
- Visual evidence of the flood such as flood stones

Chapter 5 provides some examples of relevant sources of information. Sometimes it may be necessary to look outside the actual catchment to find interesting flood events for a new flood scenario. Still, the basic flood event must be transferable from one river basin to another. In other words, the different flood and river basin characteristics must be considered. For instance, the extreme case of a monsoon flood in India is clearly an unsuitable basis for a flood scenario in Norway. Even within the same region, it may not be relevant to compare the experience of a flood event from one dam to another. Both the hydrology and the operational experiences from the lower reaches of large river systems may be irrelevant for smaller catchments near the headwaters. The most severe floods of the main rivers of Norway's largest river systems are typically caused by a combination of snowmelt and long duration rainfalls, while extreme floods in the smaller sub-catchments are usually generated by intense rainfalls causing discharge to rise rapidly. Natural hazards and secondary effects in the catchment are also relevant only as long as catchment characteristics are comparable.

Knowledge and experience of handling severe floods gained by dam operator staff at the dams in question should be emphasized. Many dam owners have good reporting routines and relevant operator experiences can thereby be found in internal reports. However, whether such reports are available or not, interviews with dam operators should be considered to reveal possible operational problems. One should bear in mind, though, that interviews or written reports taken some time after a flood may have unpleasant facts suppressed, as was revealed by the investigation of the 1995-flood in Norway described in Section 5.9. Typical melt generated floods of long duration will probably cause problems that differ from those generated by rainstorms. For many dams, no relevant operational experiences can be expected to be available. Operational experiences can, however, be gathered from other dams and river systems as long as the characteristics of the flood, dams and administrative systems are comparable.

Information on so-called "external disturbances" is best collected from the dam owner organization or others in the vicinity that have recently experienced floods. When no recent experiences are available, media representatives can be asked how they would respond to a severe flood and possible associated emergency situations. It is important to evaluate both national and local media coverage. Inquiries from stakeholders can be evaluated by combining knowledge about the local community with flood experiences from comparable areas (with similar types of settlements and infrastructure). Stakeholders include landowners, local authorities and itinerants (for example tourists).

6.4 Application of scenarios for dam safety analyses

It is hoped that detailed flood scenarios can be used in dam safety analyses in order to evaluate the full extent of floods. An analysis method should be applicable not only for single dams, but also for systems of interdependent dams. The literature review on risk analysis for dams presented in Chapter 3 did not reveal any suitable methods. The main objection against the described methods is that they are based on simplified scenarios where, for example, the flood is only represented by its peak discharge and peak water level. In addition, very few analyses have considered the human factor, and few, if any, analyses have emphasized the importance of the geographical extent of floods. The same problem was recognized by Jenssen (1998) in his study of the vulnerability of infrastructure to major floods. Jenssen therefore developed an analysis method suitable for his case. Jenssen suggests that the analysis should be split into two stages:

- A general analysis to identify which parts of the infrastructure are vulnerable to flooding
- A specific analysis which focuses on the vulnerability of a specific area to floods

This two-stage approach is similar to the approach recommended in the CRIOP-project described previously. The first stage includes an analysis for each type of infrastructure (roads, water supply system and so on). The findings from this stage are the basis for further analyses of each kind of infrastructure in the entire area. The idea of performing the analysis in two stages, like in the CRIOP-method, is sound. However, Jenssen's method has been found difficult to adapt to dams. One reason is that human actions are not included. Another is that the method is found to be complex and extensive.

The CRIOP-method is more relevant for the purpose presented here than Jenssen's method. Contrary to Jenssen's method, the CRIOP-method includes an analysis of human actions, as it emphasizes a control center's (operator's) *handling* of a crisis situation. The offshore control center is comparable to a dam operation center. However, the offshore system has limited geographical extent, and communication problems between the operation center and other parts of the system, is not the main concern, as it may be during a flood in a river basin. Dam operation centers are normally located far from the dams. In some cases, the dam operation centers are of minor importance to the outcome of the flood, either because of communication problems or the responsibility for flood handling being taken over by a water management association (Lundquist 2001b). In other words, when assessing flood handling, it is probably more interesting to focus on the local dam operators and their working environment than on the dam operation centers. Another difference is the number and location of actors, which is limited and easy to define for an offshore system. In the case of flood handling, it may sometimes be difficult to overview all the actors. There may be many actors within the dam owner organizations, as well as external actors such as other dam owner organizations in the same basin, national and local authorities, rescue teams and property owners.

A system composed of a single dam and its appurtenant structures may fit within the framework of the CRIOP-model in spite of the problems mentioned above. Two possible applications have been found:

- Application of the General Analysis only (the static analysis) to reveal weaknesses in the working environment of dam operators (local or at the operation center)
- Application of the whole CRIOP-method to analyze the local dam attendant's/operator's ability to handle a flood at a specific dam

The General Analysis is based on simple methods, preferably checklists, which focus on the working environment of the operators. The General Analysis should probably be complemented by separate risk analyses focusing on the structural safety of each dam and its appurtenant structures. Obviously, one important aspect is not covered fully: the possibility of analyzing a system of interdependent dams. The Scenario Analysis, including the STEP-diagram, is not practical for analysis of a flood scenario in a river system with several dams. The main problem is to represent the dynamics in a river system during a flood and to keep an overview of the analysis as it proceeds. In any case, the CRIOP-method cannot be used alone, but must be accompanied by a model of the river system for simulation of flood effects.

The RIFA-simulator developed for emergency training (see Section 4.6.2) may be interesting as a tool for scenario display and analysis. It is believed that RIFA will allow for simultaneous simulation of several dams in a river system. Further development of RIFA for analysis of flood scenarios has not yet been done. According to Alfredsen (2002), RIFA may be adjusted to include statistical methods, that is, simulations of a number of combinations of parameter sets. The probably most serious problem with RIFA is to calibrate human activity and events outside the simulated river system, which may have effects on the flood propagation and thereby on the overall outcome of the flood scenario.

6.5 Conclusion

A method for the creation of flood scenarios is suggested. The basic idea is to use a basis of real flood events to increase the credibility of the emergency exercises and analyses. These events, particularly from the distant past, may need to be adapted to the present, which can be done by using experiences from relevant recent floods. In some cases there may also be a need for geographical adjustments. Creation of scenarios according to the proposed method includes retrieval of data from a variety of sources. Processing data by means of hydrologic or hydraulic models or both will normally be necessary. No appropriate methods for analysis of the created flood scenarios have been found, but the newly developed RIFA-simulator seems to be promising.

7 VINSTRA RIVER BASIN – CASE STUDY

7.1 Introduction

The method proposed in the previous chapter for the creation of flood scenarios, has been tested for the Vinstra River Basin, see Figure 7.1 and Appendix D.

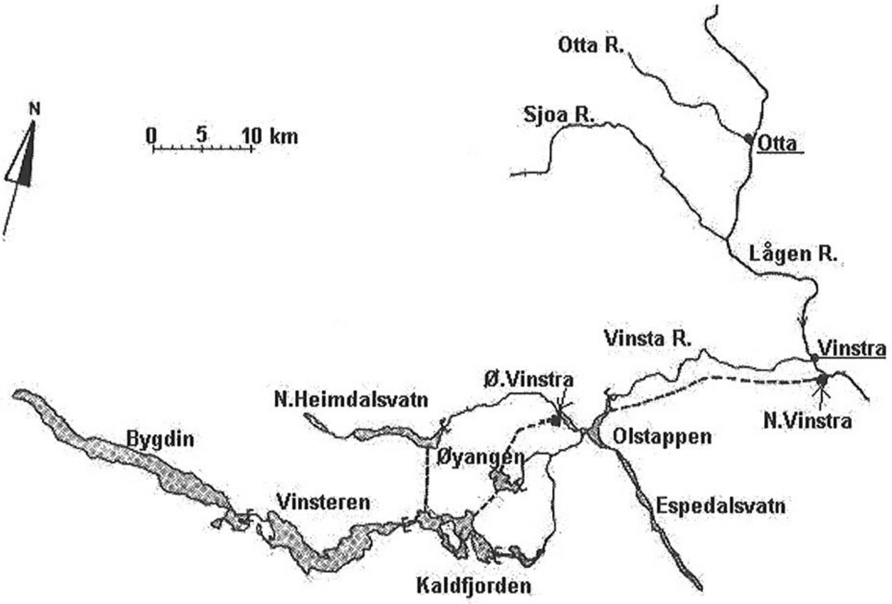


Figure 7.1 Overview of Vinstra River Basin (GLB)

The Vinstra River Basin is located in South East Norway. The Vinstra River is a tributary of the Gudbrandsdalslågen (Lågen) River with 6 reservoirs from Bygdin (1057 m asl) to Olstappen (668 m asl). The dams of the Bygdin, Vinsteren, Kaldfjorden and Olstappen reservoirs are classified as high consequence class dams. There are two hydropower plants, Øvre Vinstra and Nedre Vinstra. Most of the reservoirs are situated on a mountain plateau surrounded by high peaks and glaciers from the west to the north rising to about 2300 m asl. The only exception is Olstappen, which is located at the upper end of Vinstra Valley with steep slopes around the reservoir rim. The

Kaldfjorden and Olstappen reservoirs are surrounded by forest, but the forest around Kaldfjorden is not very dense and consists mainly of mountain birch. The four main dams in the Vinstra River Basin, Bygdin, Vinsteren, Øyvassoset (Kaldfjorden) and Olstappen, have gated spillways, some in combination with a free overflow crest. The dam at Vinsteren also has a spillway section with vertical beams. See Table 7.1 and Appendix D for more data and photographs of the main dams and reservoirs.

Table 7.1 Pertinent data for the main dams of the Vinstra River (Lundquist 1997)

DAM	Dam type - dam height [m]	Reservoir volume [m^3]	HRWL [masl]*	Q1000 (outflow) [m^3/s]	Design water level [m above HRWL]
Bygdin	PG/ER – 2.5	336×10^6	1057.63	191	1.7
Vinsteren (Bjørnhølen)	ER/PG – 9.5	102×10^6	1031.73	256	1.6
Kaldfjorden (Øyvassoset)	CB/ER – 12	76×10^6	1019.23	283	2.0
Olstappen	CB - 26	31×10^6	668.23	701	3.0

* According to revised heights, which are 0.23 m above previous local heights.
Codes for dam types: PG – Concrete gravity, CB – Concrete buttress, ER - Rockfill

The river reach from Olstappen Dam to the confluence with Lågen at Vinstra (225 m asl) has an average gradient of 1: 60. Most of the settlements and the main road along the river are on the north side of the river valley, at a height presumed safe (200-300 m) above the river itself. However, the valley-sides are steep and vulnerable to landslides. The dam owner, Glommen and Lågen Water Management Association (GLB), has developed an emergency action plan for the dams of the Vinstra River. The emergency analysis is based on checklists for adverse incidents. Each dam was analyzed separately. The spillway gates at Vinsteren Dam and Olstappen Dam have been subject to more comprehensive analyses as part of the Dam Safety Project (Sveen 1992), but the results from these analyses are not regarded as final (Rognlien et al. 1995). Furthermore, Øyvassoset Dam (Kaldfjorden Reservoir) has been analyzed as part of a project with the objective to assemble experiences from analyses for the preparation of EAP's (Honningsvåg et al. 1996). Contrary to many other dam owners, GLB has already had two major emergency exercises.

During a flood, operation of reservoirs for optimum production is of low priority. The overall aim will be to reduce flood damage without violating the concession operation procedures. Operation is also governed by legal requirement stating that floods in a regulated river basin should not cause more damage than they would have done before regulation, unless permission is given as part of the concession operation procedures (OED 2001). An exemption from the concession operation procedures or from the Water Resources Act can be granted from NVE. GLB's head office takes over responsibility for any operations throughout the Vinstra River Basin when a flood is developing. In addition, local dam operators will be placed at the four main dams (minimum one operator at each dam) according to GLB's emergency procedures. The reservoirs can be remotely operated from GLB's head office in Oslo, the operation center at Lillehammer or the local operation center at Olstappen Dam. During flood, the gates will be operated from the head office in Oslo as long as communication lines are functioning. The gates can also be remotely operated from the local operation center at Olstappen Dam. In case of a communication failure between Olstappen and the other dams, the local dam operators will follow operation procedures based on registration of changes in water levels.

7.2 Floods in the Vinstra River Basin

The reservoirs in the Vinstra River Basin were developed from 1920 (Bygdin) to 1954 (Olstappen). Like most other dam owners, GLB has experienced that floods less severe than the design floods can cause problems. An example is the 1987 autumn flood in the Vinstra River described in Section 5.8. That event had an estimated return period of 30 years, and GLB experienced several problems with spillway gate operation and monitoring of reservoir water levels. The problems originated from disruptions in electricity supply, telecommunication and road connections. The strong wind combined with rain and low temperatures also restricted access and made necessary actions difficult to perform at the dam sites in the mountains.

In contrast to most of the Glomma and Lågen River Basin, there was no flood worth mentioning in the Vinstra River Basin during May/June 1995. According to the local dam operators in the Vinstra River Basin (Midttømme 1999), the most challenging floods, like 1987, are those generated by heavy rain in combination with melting snow (Figure D-9). Two flood events are of special interest in Vinstra River Basin due to their magnitudes and impacts on the local area: the floods of 1789, Storofsen (Section 5.2) and 1938 (Section 5.4). Both events occurred during summertime and were characterized by thunderstorms with heavy rain.

7.3 Creation of the Storofsen-scenario

According to the descriptions given in Section 5.2, the flood of 1789, Storofsen, was exceptional in Vinstra River Basin. Storofsen is therefore interesting as a basis for a flood scenario. The inflow to Vinstra River Basin during the 1789 flood has been estimated by GLB (Tingvold 2000; Midttømme and Tingvold 2002). GLB has used an operational hydrological model developed for the entire Glomma and Lågen River Basin (41 200 km^2). The model is composed of several HBV-models and a routing-model (GLBRUT). Daily precipitation data from 1938 are available from several locations in the river basins as well as water level and discharge records. These data have been used for calibration of the model with good results. An example of calibration is shown in Figure 7.2.

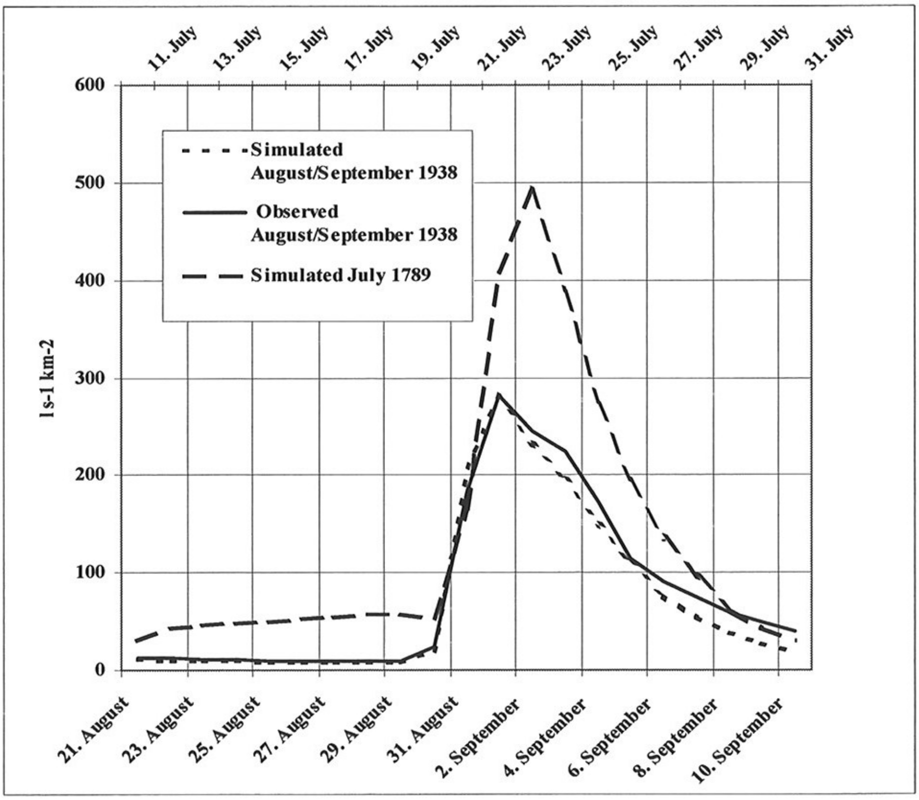


Figure 7.2 Calibration of HBV-model and reconstruction of local inflow to Olstappen in 1789 (Midttømme and Tingvold 2002)

Results from GLB's simulation of inflow and natural discharge from the unregulated lake Bygdin, and two alternative discharges from the present Bygdin reservoir are shown in Figure 7.3. The corresponding initial water levels are (with reference to the hydrographs):

- Natural discharge and discharge alternative 1 → 1056.3 m asl
- Discharge alternative 2 → 1054.8 m asl

Highest regulated water level (HRWL) in Bygdin is 1057.63 m asl corresponding to a reservoir volume of 336 million m^3.

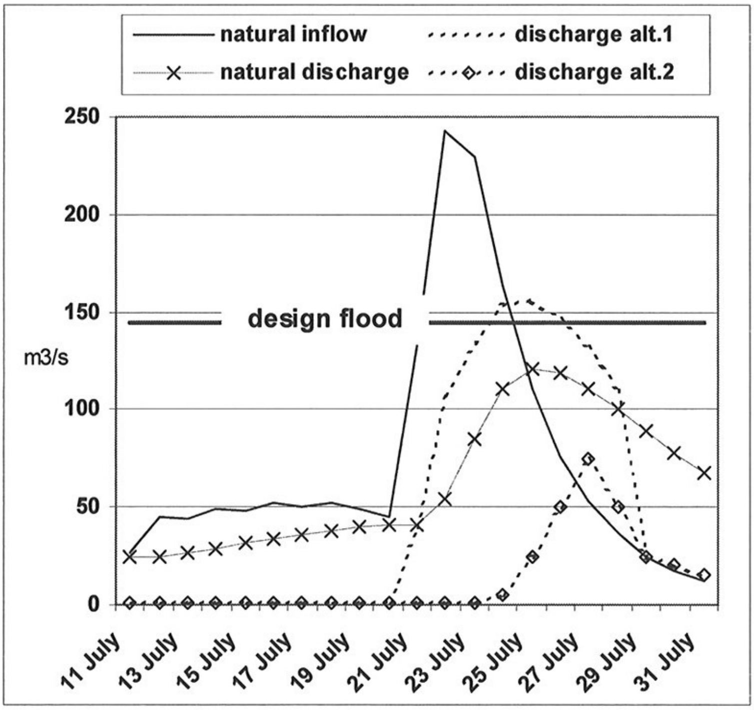


Figure 7.3 Simulation of 1789-flood at Bygdin (Tingvold 2000)

Further results from the simulations are shown in Appendix D. The results from the GLBRUT simulation indicate that the 1789-flood could be handled in the now-regulated Vinstra River System without causing dam failure. An important condition in the GLBRUT simulation is that all dam and spillway gates, as well as power plants, are operable during the flood. The flood simulations of the unregulated river system indicate a peak discharge of 4 500 m^3/s at Losna in 1789, which is in good accordance with registered water levels as discussed in Section 5.2. The inflow hydrographs, the prevailing weather conditions (see Section 5.2) and the landslide activity form the basis of the Storofsen scenario. The landslide activity was extensive in the Vinstra valley according to Sommerfeldt (1972). Possible landslide activity around Olstappen reservoir, such as in the ravine in the valley of Jodalen (see Appendix D), has the greatest emphasis in the Storofsen scenario. According to the method proposed for creation of flood scenarios, several more features should be added (see Section 6.3.1). Relevant secondary effects and additional natural hazards can be found by studying the flood of 1938, which is comparable to the 1789 flood with respect to weather conditions, time of year and flood duration.

Relevant references and a description of the 1938 flood were given in Section 5.4. Note that catchment characteristics of the neighboring river basin to the north (Sjoa) are to some extent comparable to the catchment characteristics of Vinstra River Basin. Operational experiences from the 1938 flood are available from the Bygdin Dam, but these are of very limited interest as the dam was reconstructed in 1982 (Rognlien et al. 1995). The major development of the river system as it appears today was completed in 1954, but some changes have been done after, such as upgrading of the Nedre Vinstra Hydropower Plant in 1989 (Tøsse 1991). The administrative system and the dam owner organization have, of course, developed since 1938 and are not comparable with the present system and organization. The flood of October 1987 is therefore the last significant flood of relevance in this context. Thus, additional information has been collected from logbooks and reports from this flood, from emergency analyses and from interviews with dam personnel. Some of the conclusions for inclusion in a scenario were that:

- A maximum of four dam attendants will be available for placing at the dams (meeting place: Olstappen Dam)
- Extra personnel from the hydropower plants will only be available if they are not busy handling problems with power transmission lines or operation of the power plants
- Access roads to dams and power stations will be damaged at an early stage of the flood
- Telecommunication lines are not reliable during extreme weather and regular telephone-lines and cellular phones must be expected to fail
- Automatic water level monitoring will probably not be possible. Manual readings in the reservoirs will be difficult due to weather conditions
- Both regular and auxiliary power supply, for operation of spillway gates among others, will be unreliable

- Extensive lightning activity often results in broken transmission lines. Only N. Vinstra power plant is able to produce power if the regional grid fails. Production capacity in N. Vinstra will then be reduced

Some of the secondary effects included in the Storofsen-scenario are:

- Impassable access roads at several locations
- Power failure due to lightning strike
- Malfunctioning of the auxiliary power supply units at the Bygdin Dam and Olstappen Dam
- Problems with remote observation of reservoir levels
- Outage of Øvre Vinstra and Nedre Vinstra power plants
- Communication problems (telephone)
- Landslides at several locations
- Debris in the Olstappen reservoir

Finally, external disturbances were added to the scenario. Experiences with media coverage from the flood of 1995 were utilized. The external disturbances appear as inquiries from national and local newspaper journalists, a local radio reporter and various stakeholders in the area. It would probably have been relevant to include national radio and TV-reporters as well. External disturbances can also be added independently of the flood as it progresses in order to increase the stress in an exercise or training session. More details on how the Storofsen scenario in Vinstra River Basin was created can be found in a separate report (Midttømme 2001).

7.4 Credibility of the Storofsen scenario

The credibility of the Storofsen scenario is difficult to ascertain. One option is to perform a comprehensive functional exercise, which could be evaluated by experienced personnel within GLB with respect to the realism of the script. The value of such a test would probably not warrant the necessary effort and expense. Therefore, RIFA is an interesting option. RIFA (see Section 4.6.2) was developed in parallel to this study on the creation of flood scenarios, and cooperation between the two projects was mutually beneficial. A river system model for Vinstra was built as part of the RIFA-project (Alfredsen and Midttømme 2001), based on a previous study of the effect of regulation on floods in Glomma and Lågen River Basin (Wathne and Alfredsen 1998; Alfredsen 1999). The representation of the river system is shown in Figure 7.4. It should be noted that RIFA does not provide routines for detailed and precise simulation of the river system, but appropriate methods are included to provide a realistic flood scenario for the rest of the "game" to build on. Inflow series can be simulated within RIFA as it contains routines for rainfall-runoff simulations, but previously estimated inflow series (see Section 7.3) have been used as input in this case. Routing in reservoirs is done through a mass balance method, while river routing is handled through a set of hydrological and simplified hydraulic methods as described in detail by Alfredsen (1999).

The script for the Storofsen scenario is presented in a separate report (Midttømme 2001). The current version of RIFA for simulation of Storofsen in the Vinstra River Basin contains an extract of this script. The simulation time is four days with a time step of one hour. The simulation starts one day before the flood event, on 19 July, to orientate the user to several situations associated with resource management, flood warnings and release planning issues. For users unfamiliar with the operation of the Vinstra River System, the Storofsen scenario can probably be run many times before the training effect decreases. When simulations with the same scenario are no longer challenging, the set-up should be altered. The current Storofsen version can be altered by, among others, editing the script-file, or changing initial conditions. As an example, a malfunction of the auxiliary power supply and subsequent inability to operate gates can occur at any of the dams according to information from the local dam operators, however, the Storofsen scenario currently in use in RIFA (Midttømme 2001) allows malfunctions only at the Bygdin and Olstappen dams.

Dam failure is normally the end event of an analysis or a dam emergency exercise in which handling of a natural flood is emphasized. However, in some cases a failure during an extreme natural flood can be acceptable and could therefore be included in the analysis or the exercise. The estimated inflows indicated that an event like the Storofsen scenario could cause dam failures in the Vinstra River Basin. Preliminary results of dam break flood wave calculations for the Vinstra River Basin show that a failure of Bygdin Dam could possibly be "accepted" during an extreme flood, as the downstream consequences would be moderate. Failure of any of the other dams, however, will probably affect downstream dwellings or important infrastructure to such an extent that failure should be avoided by all possible means. As the focus of this study has been on the ability of dam operators to handle severe (natural) floods in order to avoid dam failure, it was decided that failure of any of the dams should be regarded as an end event ("game over").

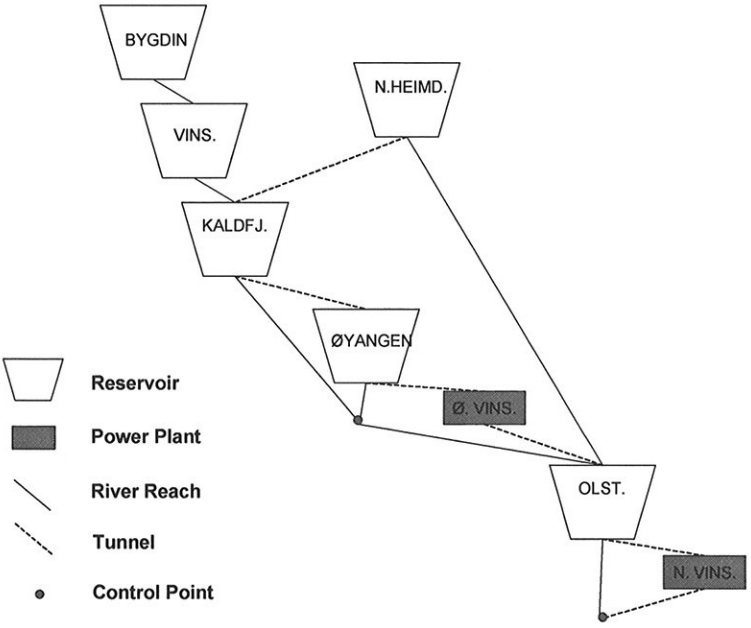


Figure 7.4 Schematic overview of reservoirs and power plants for simulation of flood handling in Vinstra River Basin

7.5 Examples from the Storofsen script and simulation

The script for RIFA contains messages to the user and alternative, multi-choice responses. There are two types of messages; messages set to a fixed time or messages controlled by fixed critical levels. Some examples from the Storofsen script are given below. A typical critical water level is the level causing damage to an access road or dam failure, for example:

Message:

> *"Water is running over the northern concrete dam at Øyvassoset and the access road to the dam attendant's house will soon be inundated"*

Alternative responses:

1. *No problem, keep on operating according to instructions*

2. *Check whether there are people in the house and if so, whether they can be evacuated from the premises*
3. *Open the intake gate in the reservoir to lower the water level*

A critical discharge can, for example, be one that leads to damage to a downstream road:

Message:

> *"Discharge from the Bygdin reservoir is causing extensive damage to road 51"*

Alternative responses:

1. *Close the road immediately, keep on operating according to instructions*
2. *Notify the Public Road's Authority*
3. *Close one spillway gate in Bygdin Dam to decrease the discharge*

Critical limit messages will be issued automatically when the flood routing results in the specified limit. Time-dependant messages will be issued at a specified time, no matter how the flood is propagating throughout the river system. The first day of simulation, it is normal to supply disruptive messages and messages carefully indicating that a flood is imminent and may develop into an extreme event.

One disruptive message in the Storofsen simulation is a telephone call from a radio reporter asking about a reported burglary in a building belonging to the dam owner. Disruptive messages of this kind, either related to or totally independent of the flood event, are added to cause stress to the user. As the flood event develops, more and more flood related messages appear. The challenge for the user is to identify the most important messages (regarding safe operation of dams and power plants) and to give the optimal response regarding the entire river system. A typical less important message could be:

Message:

> *"The mountain road between Bygdin and Vinsteren has been destroyed as a result of erosion caused by streams flowing across it. A tourist bus is stuck and needs assistance. Can you send someone to help?"*

Alternative responses:

1. *Send the dam attendant stationed at Vinsteren with his tractor.*
2. *I'm sorry, but you must call for Road Assistance and evacuate the passengers yourself to the Haugseter hotel. It is only a short distance to walk.*
3. *Reduce the outflow from Bygdin by 50 %.*

In this case, alternative 1 will prevent the user from manually operating gates at the Vinsteren Dam at a later stage, because the dam attendant will be unavailable. Alternative 2 is the optimal response and alternative 3 makes no sense, because a reduction in outflow from Bygdin will not have any effect on this situation.

A typical important message is one that affects the increase in water levels in the reservoirs, for example:

Message:

> *"Power production at Øvre Vinstra and Nedre Vinstra has stopped because of failure of regional grid"*

Alternative responses:

1. *We will watch the situation, but there is no need for any deviations from the planned operation of spillway gates and intake gates*
2. *Open all the spillway gates at Olstappen*
3. *Close the brook inlets on the headrace tunnel to Nedre Vinstra, to prevent inflow to Olstappen*

Alternative 1 will be hazardous at a time when the flood has developed to an extreme event. The other alternatives have to be weighed against each other, and a good knowledge of the river system will be of great value in this case.

Initial water levels in the reservoirs have been set to HRWL in the RIFA set-up according to operational experiences. The initial water level in the most upstream reservoir, Bygdin, however, may be lower than HRWL on 20 July (Tingvold 2001). Thus, for further studies it may be relevant to simulate Storofsen with various initial water levels for Bygdin. This can be utilized when the scenario should be changed to maintain the training effect. If the main objective is to simulate or analyze how Storofsen would affect the regulated Vinstra River Basin, changes in the scenario should be restricted. The descriptions of the basic event, conclusions from dam safety analyses, and operational experiences should govern the changes possible. However, introduction of new secondary effects not anticipated during analyses or experienced by dam operators may also be considered.

An example of a screen dump from a Storofsen simulation is shown in Figure 4.1, and a logging-file is shown in Appendix D. A fixed release pattern is used as the basis of the simulation (that is release through bottom outlet gates and intake to transfer tunnels and power plants). In addition, the user has the ability to actively operate spillway gates to increase outflow from the reservoirs. It should be noted that RIFA for Vinstra River Basin is set up with local heights. This implies that heights should be increased by 0.23 m for comparison with for example Table 7.1. The RIFA simulations have been evaluated by GLB (Lundquist 2001b), and it was concluded that the hydraulic simulations in RIFA agreed well with simulations from their operational routing-model (GLBRUT). Comparisons were made with similar input data, initial conditions and release patterns.

7.6 Conclusion

An extreme flood scenario has been created for the Vinstra River Basin, which includes four high consequence class dams. The famous 1789 flood called Storofsen was selected as a basis as it is the largest flood known of in the region. The Storofsen scenario was based on available data, which are mostly qualitative. Quantitative meteorological and hydrological data have been derived from detailed descriptions of the weather situation in 1789. A probable simulation of the 1789 flood was done by GLB and validated against registered water levels with good results. The scenario was extended with descriptions of prevailing weather conditions and landslide activity in accordance with the descriptions of the 1789 flood. Furthermore, secondary effects on the dam system, and disturbances from the media and others, were added in compliance with findings from studies of recent flood events. Results from dam safety analyses and experiences of dam operators in the basin were also utilized when selecting relevant secondary effects for the Storofsen scenario.

The scenario was tested with the RIFA-simulator, a tool for training dam operator personnel. Simulations with the described scenario have been used as training sessions. The outcome of the simulations varies from user to user. In all probability, the Storofsen scenario will pose a real challenge for untrained users. When the training effect of the described scenario diminishes, it can easily be altered to provide new challenges for users of RIFA.

8 CONCLUSIONS AND RECOMMENDATIONS

8.1 Conclusions

Flood handling

The main objective of this study has been to investigate severe floods and their impact on the safety of dams, especially in river systems with several dams. The working hypothesis has been that the design flood has been over-emphasized in dam safety assessments, and that there is many other important flood related factors that should be emphasized more than they have been to date. As expected, it was found that problems at dams with flood handling are not only related to peak discharges and water levels, but also numerous other factors. Some important examples are the prevailing weather conditions, secondary effects on vital infrastructure, duration and geographical extent of floods, dam owner experience of previous emergencies or emergency exercises, and the presence of adequate resources.

Measures for improvement of emergency planning and exercises

As severe floods are rare, most dam owners have no experience of such events. Studies of previous floods are one way of increasing ones competence for handling floods. Well-performed risk analyses can also be educational in some cases, but none of the available analysis methods are capable of addressing important factors such as the geographical extent of floods. Practice with flood handling can be achieved by taking part in emergency exercises and other training activities. The survey presented here of the status of emergency action planning among Norwegian dam owners, however, shows that several dam owners, especially among those classified in the low consequence class, have not started the emergency planning process and consequently have not had any exercises either. It is believed that emergency exercises and training sessions can inspire this group of dam owners, and recommendations are given for the inclusion of typical low consequence class owners in exercises meant for high consequence class owners. Furthermore, revisions of the Norwegian emergency planning guidelines should take into account the characteristics of low consequence class owners, typically municipalities and private individuals, as the present guidelines are adapted to (larger) hydropower companies.

Resources

The complexity of floods has been illuminated through case studies of historical, as well as recent floods. The flood of 1986 at Lutufallet demonstrated how seemingly manageable floods can pose a significant threat to dam safety due to the occurrence of common cause failures created by the flood or by the prevailing weather conditions. The geographical extent of floods may also place an extra burden on many dam owners, as they may need to focus more on communication and location of resources. This was demonstrated by both the 1985 flood of the Ore River, Sweden (Noppikoski-failure) and the 1995 flood at Moksa and Vinkelfallet. In these times of workforce reductions and other efficiency measures, dam owners should have at least a minimum level of their own resources for handling floods and other emergencies. Extra personnel must also be available. However, it is not enough to have a theoretically sufficient number of personnel. Having skilled personnel, adequate resources available, and an emergency action plan or procedures for handling emergency situations, is extremely important. It must be kept in mind that local dam operators often play a key role during floods.

Robust systems
Safety analyses cannot possibly identify all the kinds of undesired events that can happen during a flood. In addition, the complexity of our society is growing, and it will probably be even more difficult to assess all possible threats to our dams in the future than it is now. Technical solutions and dam owner organizations must therefore be robust in order to be able to handle severe floods.

Information plans
Information needs may vary during a flood, but are normally extensive, both within the dam owner organizations and to the media, local communities and cooperating parties. In order to avoid extra strain on key personnel, it may in some cases be wise to protect them from contact with media during the flood. A plan for disseminating information should therefore be included in every emergency action plan.

Flood scenarios
It is believed that there may be some benefits from using detailed flood scenarios as basis for both risk analysis and emergency exercises. A method for creating reliable flood scenarios has been proposed where data from previous floods can be utilized along with recent experiences and information from updated dam safety assessments. The method relies on combining various kinds of information (from hydrological data to eyewitness-descriptions), possibly from a number of similar floods, in order to create flood scenarios. The method was tested with the creation of a Storofsen scenario for the Vinstra River Basin. Testing of the scenario with the newly developed River Flood and Accident Simulator (RIFA) demonstrates that the presumably manageable Storofsen-flood poses a real challenge to dam operators when natural hazards, secondary effects and other problems are added to the scenario.

8.2 Recommendations for further studies

An extended collection of cases
The method for the creation of flood scenarios has only been tested for one river basin. Testing of the method in a river system other than Vinstra may require input data from other floods. The collection of flood events presented here should therefore be extended. An extended collection of cases will also be beneficial for risk analyses and emergency planning for dams, irrespective of scenarios being created by the proposed method. It must be emphasized that experiences gained from floods must be carefully evaluated with respect to relevance for the dam or river system in question.

The human factor
The importance of the human factor for the safe operation of dams during floods has come up in several contexts during this study. There is a need for further studies in this field, especially on the role of dam operators during floods and other severe situations. Dam owner organizations (with focus on internal affairs), and theirs dealings with other parties during a flood or other emergencies also deserve attention. The ongoing changes in society with increased interest in cost-effective organizations should be evaluated in particular. This development is on the verge of reaching a limit with respect to what is defensible from a safety and preparedness point of view.

A new analysis method based on RIFA
RIFA was evaluated as a possible tool for analysis of flood handling in a system of dams based on detailed scenarios. Any development of RIFA as a tool for scenario analysis should follow the recommendations given by Ingstad and Bodsberg (1990). In particular, this means the use of a two-stage approach, where a general analysis is performed prior to the actual scenario analysis. The general analysis should probably comprise both a traditional analysis of the separate dam structures, as well as a static analysis of the dam operator's ability to handle abnormal situations at each dam. The latter should focus on working environment, and development of checklists is required. The scenario analysis must include several flood-routing iterations, as adverse incidents included in the scenario will affect the operation of the dams. RIFA can be set up with time-dependent changes in operation of reservoirs, or changes in operation of reservoirs can be linked to exceeding of defined marginal values for water levels or discharges.

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APPENDIX A

KONTROLLSKJEMA FOR STATUS I ARBEIDET MED BEREDSKAPSPLANER MOT VASSDRAGSULYKKER.

SPØRRESKJEMA

Navn på anleggseier:			
Bruddkonsekvensklasse:	- Oppgi høyeste klasse (1, 2 eller 3) ved deres anlegg.		
BEREDSKAPSPLANER MOT VASSDRAGSULYKKER	(ja/nei)	Årstall	Når ble siste revisjon utført?
Analyseplan (bakgrunn for beredskapsplanen)			
• Er det utarbeidet en analyseplan?			
Beredskapsplan (operative plan)			
• Er det utarbeidet beredskapsplaner mot vassdragsulykker?			
• Hvis nei, når er planer ferdige?			
Innsatsplaner			
• Er det laget innsatsplaner mot vassdragsulykker?			
Dambruddsbølgeberegninger			
• Er det utarbeidet dambruddsbølgeberegninger?			
• Hvis nei, når er beregninger ferdige?			
• Er det avholdt møter med redningsmyndigheter?			
• Når er neste møte planlagt avholdt?			
Øvelser			
• Er det arrangert beredskapsøvelser?			
• Er det laget en plan for fremtidige beredskapsøvelser?			
Kommentarfelt:			

Underskrift:

Sted og dato:

Utfylt skjema bes sendt: NVE, Sikkerhetsavdelingen, Postboks 5091 Majorstua, 0301 OSLO

BEREDSKAPSPLAN-UNDERSØKELSE 2000, sammenstilling av resultater: G.H.Midttømme, NTNU

Dameier-klasse	Totalt antall (#)	Svar	Operativ beredskapsplan (BP)	Beredskaps-analyse	Innsats-plan	Dambrudds-bølgeberegn. (DBB)	Avholdt møte med rednings-myndigheter	Avholdt øvelser	Plan for øvelser	Merknader (NB! Husk gammel klasseinndeling)
Klasse 1	47	Ja	45	40	44	6	18	36	25	
		Nei	1	4	2	40	28	9	20	
		Ikke svart	1	3	1	1	1	2	2	
		Sum	47	47	47	47	47	47	47	
Klasse 2	109	Ja	82	65	74	12	13	40	25	
		Nei	7	22	15	77	73	50	58	Noen mener DBBB er unødv.
		Ikke svart	20	22	20	19	23	19	26	
		Ikke krav	0	0	0	1	0	0	0	Dameier i klasse 2 pga rørgate.
		Sum	109	109	109	109	109	109	109	
Klasse 3	114	Ja	66	48	59	0	15	18	15	5 dameiere har DBBB
		Nei	26	41	30	0	65	71	70	Noen mener BP er unødv.
		Ikke svart	22	25	25	0	34	25	29	
		Ikke krav	0	0	0	114	0	0	0	
		Sum	114	114	114	114	114	114	114	

The survey was done in year 2000 when class (klasse) 1 was highest consequence class.

General comments to the table above:

Ja = yes, Nei = no, 0 = no response, Ikke krav = not required

Column headings from left to right are:

Dam owner class - Total # - Answer - EAP - Emergency analysis - Emergency procedures - Dam break flood calc. - Preparatory meetings with local authorities - Emergency exercises - Plan for emergency exercises - Comments

APPENDIX B

Moksa River, June 1995

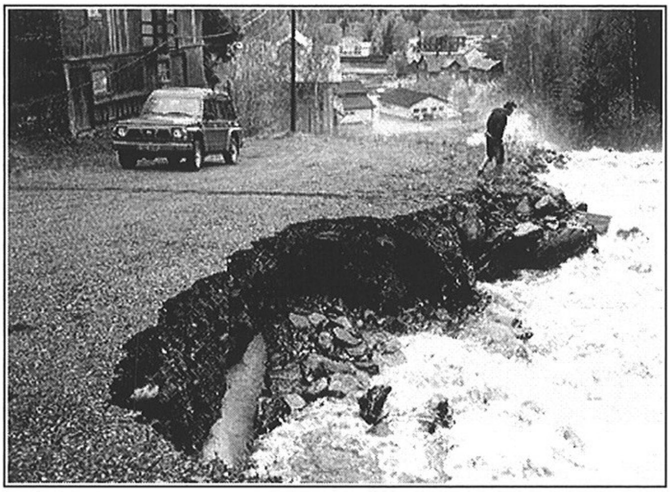

Figure B-1 The mechanical engineer inspecting the river banks close to Moksa 1 (the old power plant) on 1 June 1995 – notice erosion around the pipeline (photo: MGE)

Figure B-2 Deposits upstream of Moksa power plant after the flood (photo: MGE)

Figure B-3 Damages caused by the flood – downstream reach of the new river course

Figure B-4 The old river course, Moksa

Figure B-5 Moksa 1 and the pipeline, where the river broke through the river bank

Figure B-6 One of the houses completely destroyed by the Moksa River

Vinkelfallet Dam and Reservoir, 14 June 1995

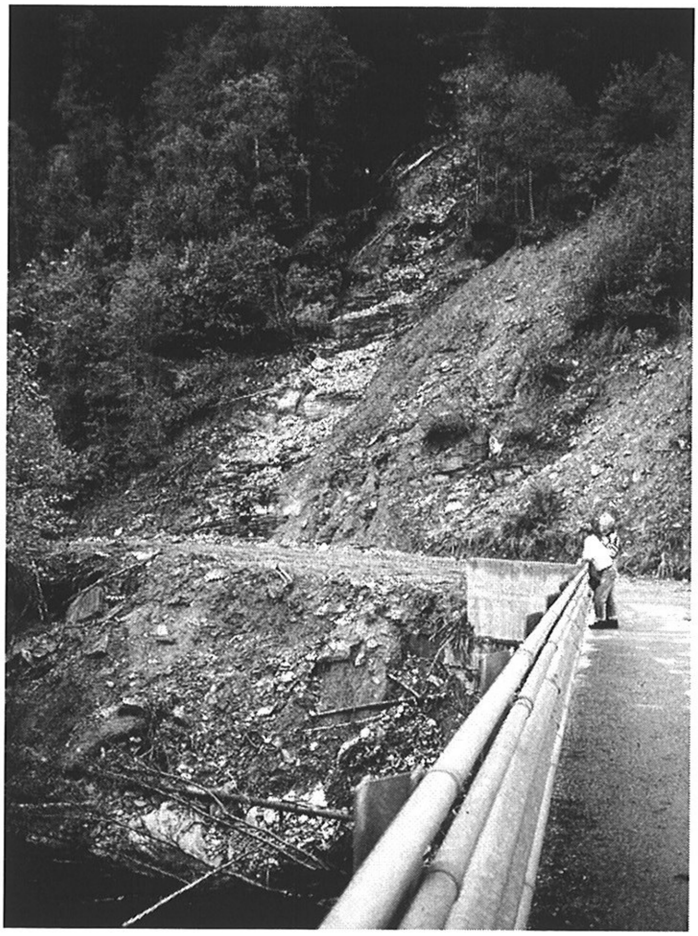

Figure B-7 Slides in the upstream end of Vinkelfallet Reservoir

Figure B-8 Slides between the road and the reservoir at Vinkelfallet

Figure B-9 Upstream of Vinkelfallet Dam

Lower Glomma during 1995 flood

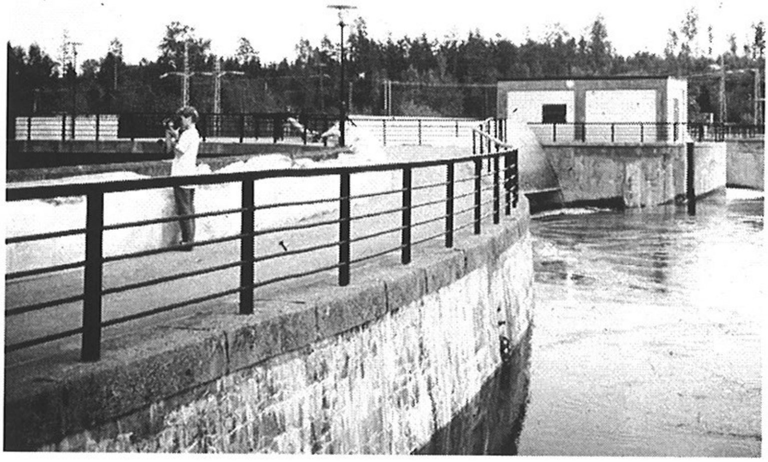

Figure B-10 Heightening of dam crest at Vamma Dam by means of sand bags (photo: H. Midttømme)

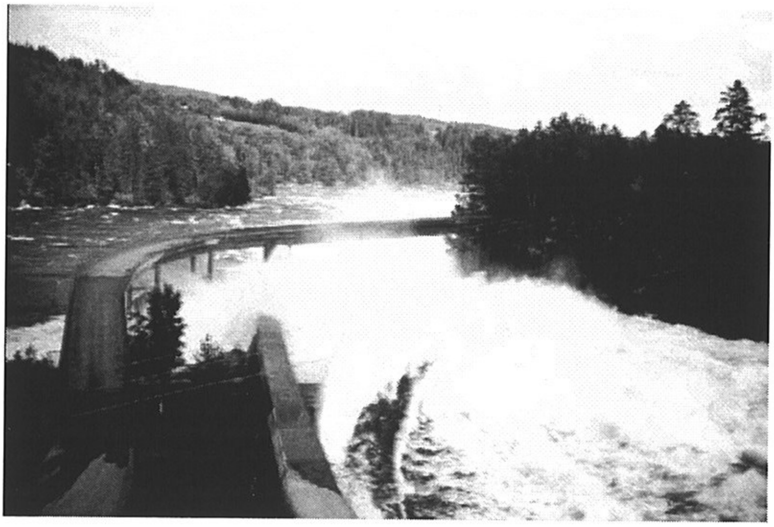

Figure B-11 Spillway channel at Vamma Dam

Figure B-12 Bingsfoss Dam and power plant, high upstream water level

Figure B-13 Solbergfoss Dam and power plant (photo: P.C.Røhr)

APPENDIX C

FIELD TRIP TO STORA GÖLJÅN RIVER AND MOUNT FULUFJÄLLET, SWEDEN IN 1999

Only a few persons were in the area of Stora and Lilla Göljån in the night of 30-31 August 1997, and they were all indoors when the rainstorm ravaged the area. They stayed in their caravans south of Lilla Göljån's conjunction with Fulan River (marked "Raststuga" in the map on the next page). Thus, there are no eyewitness descriptions from the peak of the flood. In August 1999, however, the author visited the area together with Dan Lundquist from GLB, who also visited the same area in 1998. We followed the footpaths from the parking lot at "Raststugan". After a walk along the damaged forest road and over the alluvial fan between the road and Fulan River, we walked uphill along Stora Göljån and tried to follow the footpath around the Göljån River branches. Stora Göljån was completely changed after the flash flood, but a photo from 1996 shows how the river, or more correct, the stream of Stora Göljån appeared before 1997 (Figure C-1). All the other photos are by Dan Lundquist and were taken during the fieldtrip in 1999, except Figure C-7, which was taken in 1998.

Figure C-1 Stora Göljån before the flash flood (photo: R.Lundqvist, 1996)

Appendix C

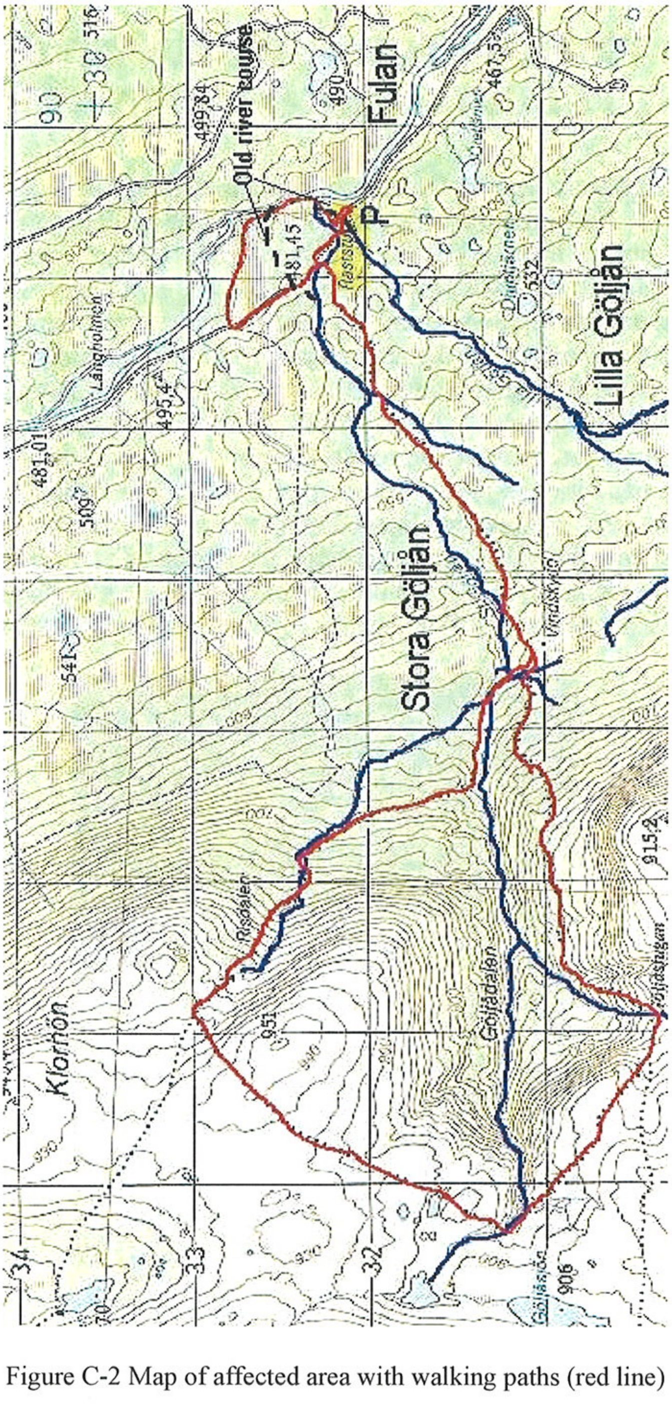

Figure C-2 Map of affected area with walking paths (red line)

Figure C-3 Road closed ahead!

Figure C-4 Looking upstream from the Stora Göljån culvert. Accumulated debris in the old river course

Figure C-5 Debris in the alluvial fan

Figure C–6 The upper end of Stora Göljån, close to Göljåstugan (looking downstream)

Figure C-7 At edge of Mount Fulufjäll, close to Göljåstugan (photo: D. L. 1998)

Figure C-8 A tributary to Stora Göljån, in the upper end of Risdalen valley

Figure C-9 Stones deposited in the middle of the forest, in Risdalen valley

Figure C-10 Deposited stones in the vicinity of the Stora Göljån branch in Risdalen valley

Figure C-11 Along the lower parts of Stora Göljån

APPENDIX D

BYGDIN DAM AND RESERVOIR

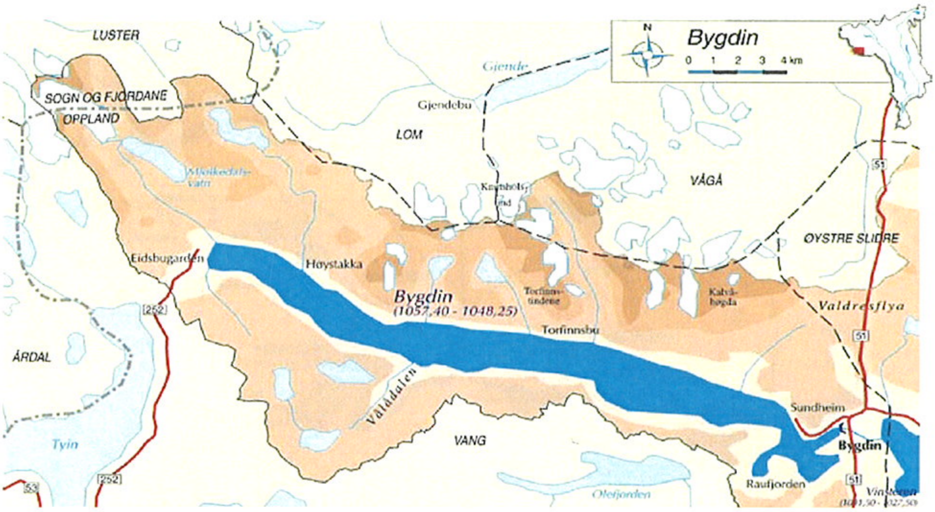

Figure D-1 Map of Bygdin Reservoir (GLB)

Figure D-2 Bygdin Dam with two radial gates

VINSTEREN DAM AND RESERVOIR

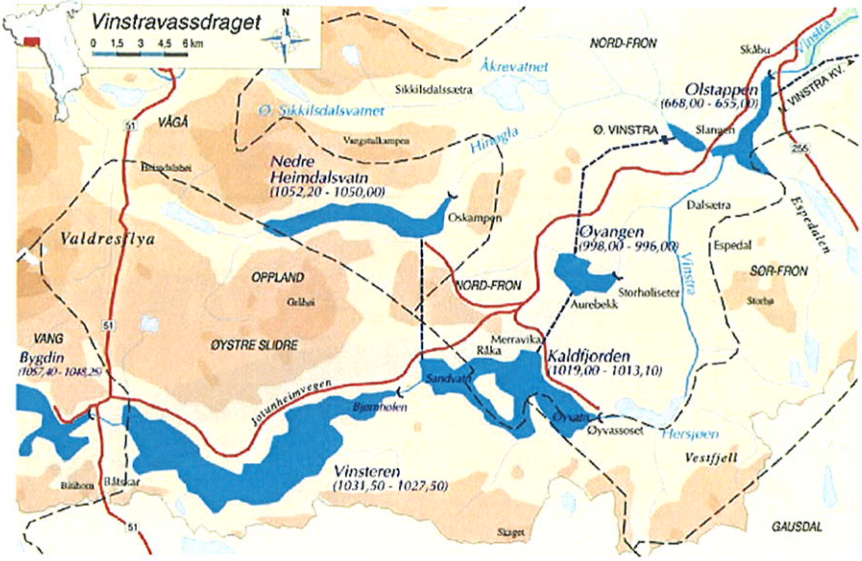

Figure D-3 Map of Vinsteren, Kaldfjorden and Olstappen reservoirs (GLB).

The road "Jotunheimvegen", which is closed during winter, is the only access road to Vinsteren and Kaldfjorden.

Figure D-4 Vinsteren Dam seen from the upstream side

ØYVASSOSET DAM AND KALDFJORDEN RESERVOIR

Figure D-5 Øyvassoset Dam and part of the Kaldfjorden Reservoir

Figure D-6 The spillway section at Øyvassoset Dam

OLSTAPPEN DAM

Figure D-7 Olstappen Dam (photo: GLB)

Figure D-8 The ravine in Jodalen, which was formed in the 1789 flood. The ravine is located north of Olstappen dam (photo: GLB)

Vinstra River Valley

Figure D-9 The 1987 flood downstream of Olstappen (at Kamsfossen) – erosion of river bank (photo: O.P.Dahle, GLB)

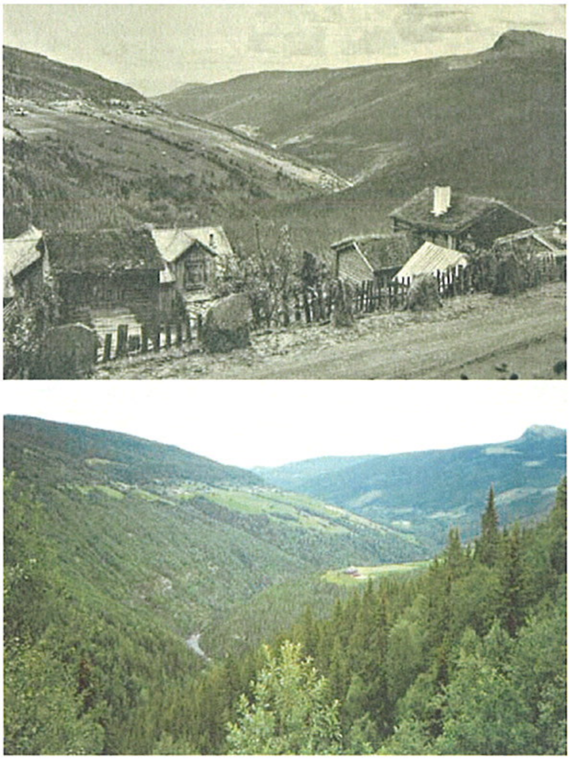

Figure D-10 The Vinstra valley (Kvikne area) in the early 20th century and in 1999

Figure D-11 Repair work on the main road from Vinstra to Skåbu (Olstappen) after erosion damage from flood in a small tributary to Vinstra River, August 2000

Figure D-12 The Vinstra valley at Graupe with settlements high above the river

Appendix D

Output file from simulation of Storofsen-scenario

The format of the log is [date_time_message] followed by [date_time_response], i.e. the message is followed by a response at the same time-step as the message. Some responses are also followed by a following-up message.

```
07/19/89 08:00:00: Værmeldingen for de neste dagene tyder
på kraftige regn- og tordenbyger.
07/19/89 08:00:00: Ok.
07/19/89 13:00:00: Damvokter Olsten har fått fri et par
ekstra dager for å utnytte godværet og fiskelykken på
hytta i Finnmark
07/19/89 13:00:00: Det er greit, men han må stille opp på
Olstappen senest onsdag 22.juli
07/19/89 18:00:00: Hytteeier ved Vinsterdammen melder om
at det har vært innbrudd i huset på Bjørnhølen i helgen
07/19/89 18:00:00: Vi sender en mann for å undersøke med
en gang
All provianten på Bjørnhølen er borte etter innbruddet
07/19/89 19:00:00: Vi sender en mann til Vinstra for å
skaffe ny proviant
07/19/89 20:00:00: Radio Tri ønsker et intervju angående
innbruddet på Bjørnhølen
07/19/89 20:00:00: Det passer litt dårlig nå, men de kan
ta kontakt i arbeidstiden i morgen
07/20/89 10:00:00: NVE har sendt ut varsel om stor flom
07/20/89 10:00:00: Ok.
Radio Tri er her igjen og vil gjerne snakke om innbruddet
i går
07/20/89 11:00:00: Jeg kan ta en prat, så får jeg samtidig
informert om muligheten for flom
07/20/89 12:00:00: Gudbrandsdal Energi minner om at det må
tas hensyn til trafostasjon ved Vinstras utløp
07/20/89 12:00:00: Vi har tatt hensyn til dette i vår
tappestrategi
07/21/89 07:00:00: Det meldes om brutt veiforbindelse ved
Massing. Har dere noe maskiner til utlån?
07/21/89 07:00:00: Vi sender en gravemaskin
07/21/89 08:00:00: Jotunheimvegen er nå helt uframkommelig
mellom Haugseter og Bygdin. En minibuss med utenlandske
turister står fast ca 1 km fra Haugseter.
07/21/89 08:00:00: Dere kan få låne en traktor
```

```
07/21/89 10:00:00: Radio Tri ønsker å vite hva som har
skjedd med bussen på Haugseter`
07/21/89 10:00:00: De må ta kontakt med info-ansvarlig
07/21/89 11:00:00: Det er problemer med tette stikkrenner
og erosjon flere steder langs Jotunheimvegen. Kan dere
avse folk til å rette opp skadene?
07/21/89 11:00:00: Vi har ingen ledige, ta kontakt med
vegvesenet eller kommunen.
07/21/89 18:00:00: VG vil ha opplysninger om flommen og
sikkerheten til dammene
07/21/89 18:00:00: Vi har andre ting å tenke på. VG får
henvende seg til info-ansvarlig
07/21/89 21:00:00: VG vil vite hvorfor GLB slipper så mye
vann til Vinstra sentrum
07/21/89 21:00:00: Vi har andre ting å tenke på. VG får
henvende seg til info-ansvarlig
07/22/89 06:00:00: Det begynner å bli en del drivgods i
Olstappen pga små ras langs breddene
07/22/89 06:00:00: Drivgodset vil bli dratt igjennom
lukene
07/22/89 07:00:00: Ønsker manuell avlesning av vannstand i
Bygdin.
07/22/89 07:00:00: Send mannskap frå Skaabu til Bygdin
07/22/89 07:00:00: Utsett dette til vi får bedre
værforhold
Drivgods setter seg fast i lukeløpet. Hva gjør vi?
07/22/89 09:00:00: Send ut noen med motorsag for å løse
opp proppen
07/22/89 11:00:00: Nødstrømsaggregatet på Olstappen
fungerer ikke. Vi får ikke manøvrert lukene.
07/22/89 11:00:00: Prøv å reparere nødstrømsaggregatet
07/22/89 14:00:00: Store mengder drivgods samler seg i en
propp ved Lo mølle. Fare for brudd og flombølge i Vinstra
07/22/89 14:00:00: Vi kan dessverre ikke gjøre noe
07/22/89 14:00:00: Ras i Jodalen. Kan dette true
Olstappen?
07/22/89 14:00:00: Dammen ligger trygt i forhold til
rasstedet
07/22/89 18:00:00: Radio Tri ønsker å vite hva GLB gjør
for å endre belastning på Lo mølle
07/22/89 18:00:00: De får ta kontakt med info-ansvarlig
07/23/89 04:00:00: Det renner vann over gangbanen på
Vinsterdammen
07/23/89 04:00:00: Reduser tappingen fra Bygdin
07/23/89 04:00:00: Olstappendammen overtoppes med fare for
at vannet ødelegger vaktbua
```

```
07/23/89 04:00:00: Send ut en mann for å vurdere
situasjonen
Er på Olstappen og det er vann overalt,  hva gjør vi?
07/23/89 05:00:00: Varsle politiet
07/23/89 05:00:00: Gangvegen fra hotellet til
Damvokterboligen på Bygdin er i ferd med å bli oversvømt
07/23/89 05:00:00: Dere bør stenge adkomsten til baksiden
av hotellet.
07/23/89 10:00:00: Det renner vann over nordre sperredam
ved Øyvassoset og adkomsten til hoveddammen kan bli stengt
hvis vannet fortsetter å stige
07/23/89 10:00:00: Sjekk om det er folk på dammen og om de
har egnet kjøretøy til å ta seg gjennom vannmassene
07/23/89 19:00:00: Vinsteren er breddfull og det strømmer
vann ut av nedstrøms damtå
07/23/89 19:00:00: Send ut en mann for å vurdere
situasjonen

(GAME OVER - FAILURE OF VINSTEREN DAM)
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Simulation of 1789 flood with GLBRUT

GLB has simulated the local inflow floods to the reservoirs Bygdin, Vinsteren and Olstappen and the coherent natural discharges. The tables presented on the following pages also include results from GLB's simulation of the 1789 flood in today's regulated river system based on a probable release pattern, and two alternative initial water levels. The inflow to Kaldfjorden is included in the inflow to Olstappen, i.e. Kaldfjorden, N.Heimdalsvatn, Øyangen and Olstappen reservoirs are represented by a combined reservoir as shown in the tables below. Outflow from the combined reservoir represents outflow from Olstappen. For simulation in RIFA it has been necessary to split the combined inflow series into separate series for each reservoir. Catchment area ratios have been used as basis, which is believed to be sufficient in this context.

Bygdin							
1789	natural inflow	reservoir natural	natural discharge	discharge alt.1	reservoir alt.1	discharge alt.2	reservoir alt.2
date	m3/s	Mm3	m3/s	m3/s	Mm3	m3/s	Mm3
11 July	27	292	24	1.3	292	1.3	225
12 July	45	292	25	1.3	294	1.3	227
13 July	44	294	27	1.3	298	1.3	231
14 July	49	295	29	1.3	302	1.3	235
15 July	48	297	31	1.3	306	1.3	239
16 July	52	298	34	1.3	310	1.3	243
17 July	50	300	36	1.3	314	1.3	247
18 July	52	301	38	1.3	318	1.3	251
19 July	49	302	40	1.3	323	1.3	256
20 July	45	303	41	1.3	327	1.3	260
21 July	132	303	41	40	331	1.3	264
22 July	243	311	54	108	339	1.3	275
23 July	229	328	85	134	350	1.3	296
24 July	164	340	111	154	359	5	316
25 July	111	345	121	156	359	25	329
26 July	76	344	119	146	356	50	337
27 July	53	340	111	132	349	75	339
28 July	37	335	100	110	343	50	337
29 July	25	330	89	25	336	25	336
30 july	17	324	78	20	336	20	336
31 July	12	319	68	15	336	15	336

Vinsteren							
1789	nat. loc. inflow	reservoir natural	natural discharge	discharge alt.1	reservoir alt.1	discharge alt.2	reservoir alt.2
date	m3/s	Mm3	m3/s	m3/s	Mm3	m3/s	Mm3
11 July	10	63	24	9	100	2.0	70
12 July	15	62	25	14	100	2.0	71
13 July	15	63	27	14	100	2.0	72
14 July	17	63	29	15	100	2.0	73
15 July	17	63	31	15	100	2.0	75
16 July	18	63	34	16	100	2.0	76
17 July	18	64	36	15	100	2.0	78
18 July	18	64	38	16	100	2.0	79
19 July	18	64	40	15	100	2.0	81
20 July	16	64	41	14	100	2.0	82
21 July	48	67	41	49	100	2.0	83
22 July	98	76	54	113	102	2.0	87
23 July	101	86	85	119	108	10.0	96
24 July	75	94	111	190	115	30.0	104
25 July	52	98	121	188	116	50.0	108
26 July	36	99	119	192	116	65.0	110
27 July	25	98	111	171	114	75.0	112
28 July	18	96	100	144	112	75.0	114
29 July	12	92	89	55	110	75.0	114
30 july	8	89	78	48	108	50.0	110
31 July	6	81	68	42	106	25.0	109

	Heimdalsv./Kaldfj./Øyangen/Olstappen						
1789	**nat. loc. inflow**	**reservoir natural**	**natural discharge**	**discharge alt.1**	**reservoir alt.1**	**discharge alt.2**	**reservoir alt.2**
date	**m3/s**	**Mm3**	**m3/s**	**m3/s**	**Mm3**	**m3/s**	**Mm3**
11 July	19	92	43	28	120	25	120
12 July	27	92	49	41	120	25	120
13 July	29	92	53	43	120	25	120
14 July	30	93	57	45	120	25	121
15 July	31	93	61	46	120	25	121
16 July	33	93	66	49	120	25	122
17 July	34	94	70	49	120	25	123
18 July	36	94	75	52	120	50	124
19 July	36	94	79	51	120	50	123
20 July	33	95	80	47	120	83	122
21 July	105	95	124	154	120	150	117
22 July	259	97	241	314	120	200	114
23 July	314	104	326	352	125	200	119
24 July	247	110	329	356	132	200	130
25 July	174	113	303	351	139	200	136
26 July	123	114	277	326	140	200	138
27 July	86	113	250	268	139	200	137
28 July	61	111	223	217	138	200	134
29 July	39	109	194	152	137	150	128
30 july	27	106	167	98	132	83	125
31 July	19	103	143	61	130	83	125