Challenges on dam safety in a changed climate in Norway

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SYNOPSIS. Much research has been done recently on the possible future scenarios of climate change. The effects on runoff and extreme precipitation for Norway have been investigated, and the results indicate that there will be larger and more frequently occurring floods in the future. Some possible effects on dam safety in Norway are presented as well as some recent examples of dam incidents caused by unusual climatic conditions.

INTRODUCTION

Over the past few decades there has been an increased interest in climate change issues. Whether climate change is caused by natural variations or man-made emissions into the atmosphere (or a combination of these two mechanisms), we should be prepared to handle possible effects of the scenarios given by the researchers. A changed climate will evidently result in changes in the basis for safety evaluation of dams and other hydraulic structures, and updating of the design flood estimations may be necessary. Today the need for updating of the design flood estimations in Norway is evaluated as part of the regular dam safety reassessments, normally every 15 years according to the guideline on inspection and reassessment. That is, when there are considerable changes in the data series that has been used for the estimation of design floods, new design flood estimations must be performed. The guideline on inspection and reassessment is one of several new guidelines on dam safety that have been published over the last few years, and more are currently being prepared or are planned in the near future. The guidelines describe how the requirements in the regulations on dam safety can be fulfilled. Today the following regulations form the legal framework for dams, all of them with a legal basis in the Water Resources Act of 2001;

- Regulations on dam safety
- Regulations on classification of dams
- Regulations on qualification requirements
- Regulations on internal control

Long-term benefits and performance of dams. Thomas Telford, London, 2004

The development of the legal framework for dams in Norway is described in a recent article by the author (Midttømme, 2003). The Norwegian Water Resources and Energy Directorate (NVE), which is the regulatory authority on dam safety in Norway is responsible for the development of the new guidelines.

FLOOD ESTIMATION

Around 1980 major changes in the flood estimation methods were introduced in Norway. This resulted in a need for updating of the design flood and probable maximum flood (PMF) estimation for most Norwegian dams. Since then, new flood estimations have been carried out for more than 800 dams (the total number of classified dams is approximately 2300), sometimes followed by upgrading of the dam structure or spillway (Pettersson 1998). A new guideline on flood estimation was prepared as part of the recent revision of the legal framework on dam safety mentioned above. This new guideline requires 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 new general revision of design flood and PMF estimation for dams in Norway. The present method for flood estimation is described briefly in the following paragraphs.

In Norway two floods are defined; for spillway design and dam safety control, respectively:

- The "safety check flood" which must be bypassed safely without causing dam failure. Some damage to the dam may be accepted.
- The "design flood" which is 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 high hazard dams the PMF is selected as the safety check flood and Q_{1000} (the flood with a return period of 1000 years) as the design flood, see Table 1 below.

The PMF is calculated by use of rainfall/runoff models on the basis of estimates of probable maximum precipitation (PMP). 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.

Table 1 Selection of floods in current Norwegian dam safety regulation

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

The 1000-year flood is defined in the guidelines as "*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*". For routing through the reservoir in order to find the design outflow flood and the corresponding water level, one of the general requirements is that initial water stage in the reservoir be set to the highest regulated water level (HRWL). Transfer tunnels for water into the catchment are normally considered open, while transfer tunnels out of the catchment are considered closed. More details about requirements and methods for flood estimation can be found in the guidelines (NVE 2002) and in an article prepared for the ICOLD European Symposium in Barcelona in 1998 (Pettersson 1998).

SEASONAL AND REGIONAL FLOOD CHARACTERISTICS

Norway is a country with distinct seasonal and regional variations of climate and runoff. The variability in floods over the year and from region to region is exemplified by two catchments shown in the figure below. 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 duration than autumn floods, but there are exceptions. Typical areas dominated by spring floods are Southeast Norway and Finnmark, the northernmost county of Norway (on the mainland). In coastal areas there may be no seasonal distinction between spring floods and autumn floods. Floods may appear at any time of year, and summer is 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 is floods during summer (Sælthun 1997).

Many rivers are regulated and the purpose of most Norwegian reservoirs and dams is hydropower production. Consumption of water from the hydropower reservoirs 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.

CLIMATE AND RUNOFF SCENARIOS FOR 2030-2049

As part of the research project RegClim, the global climate scenarios developed by IPCC (The Intergovernmental Panel on Climate Change) has been downscaled in order to prepare for impact studies of climate change in Norway. The most probable scenario, according to the RegClim-project, is that the annual temperatures in Norway will increase by 0.25 C/decade up to 2050 (Iversen, 2003). It may be worth noticing that the increase in temperature is estimated to be highest in the winter months and in the northern parts of the country. There is also an expected increase in annual precipitation for the whole country, and the highest increase is estimated to occur in the western part of Norway in the autumn. A minor increase in wind velocities and the number of storms is also expected, especially in Central Norway.

Based on the results from the RegClim-project, work has been done to estimate annual and seasonal runoff for the period 2030-2049 (Roald et.al. 2002). The runoff scenarios are based on two modelling strategies, i.e. modelling by the use of two different versions of the HBV-model for 42 catchments in Norway. Both modelling approaches are based on the same rainfall/runoff model. A comparison of the change in runoff simulated by the two models, show that the difference is generally quite small. The results differ by 2% or less for 30 of the 42 catchments. With a few exceptions, the results show a general increase in annual runoff for all the catchments for the period 2030-49 compared with the control period 1980-99. The highest increase in annual runoff is estimated to 20% in the western part of Norway. A study of the simulated changes of the seasonal runoff show that the winter runoff will increase significantly in the southern part of East Norway and in catchments along the coast of West Norway. The spring runoff will increase in the inland and the mountainous part of most of Norway, but the highest increase will be in the coastal catchments of Finnmark, the northernmost county of Norway. The summer runoff will decrease in most of the catchments, while the autumn runoff will increase in West Norway and Finnmark. More details are shown in Figure 1 below.

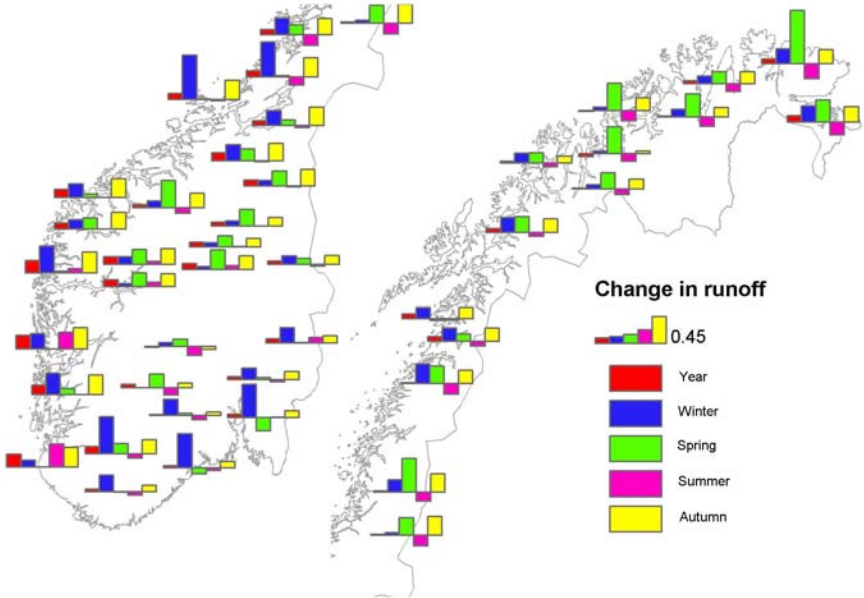

Figure 1: Seasonal changes in runoff for scenario-period 2030-49 compared to control-period 1980-99 (Roald 2003).

Scenarios of extreme precipitation of duration 1 and 5 days due to climate change have also been developed for Norway (Skaugen et.al. 2002). Time series of 1000 years have been generated on basis of downscaled precipitation values from a global climate model. The study indicates an increase in extreme values and seasonal shifts for the scenario period 2030-49, compared to the control period 1908-99. The study is based on simulations at 16 locations in Norway and the results show a significant regional variability.

POSSIBLE EFFECTS ON DAM SAFETY

The majority of dams in Norway were designed and constructed long before the first dam safety regulations were made valid in 1981. Even though many dams and spillways have been upgraded already to meet the present safety standards given in the new legal framework (see above), there is still a need for upgrading and rehabilitation of many dams, also as a consequence of damage due to deterioration and ageing processes. Floods and extreme weather will cause extra strain on dams and spillways, and the latest results from the studies of climate change and effects on runoff and extreme precipitation indicate that we should be prepared for more extreme weather and larger and more frequently occurring floods. For spillways that have rarely been in use so far, it should be noted that damage in the spillways might occur at discharges much lower than the design flood (Kjellesvig 2002). Recent studies on damages to concrete dams, which is the leading dam type with respect to number of dams in Norway, showed that 5 % of these dams had damages, which were considered to be a threat to the overall safety. It is also worth noticing that 44 % of the Norwegian concrete dams had been repaired already, and that 40% needed repair in the near future. There were also several reports about dams that had been repaired more than one time (Jensen 2001), indicating that the dam owners put too little emphasis in finding the actual cause of damage and/or the best repair method. In total, we may be facing a growing need for repair works in the future for all dam types. However, as there seems to be an increase in winter and/or spring runoff in larger parts of the country, it may be more difficult to find an appropriate time for doing necessary rehabilitation and upgrading works than what is the situation today. The present energy situation in Norway may also worsen the situation. There is an increasing gap between energy production capacity and energy consumption. As Norway is totally dependent on hydropower, it may be a problem to gain acceptance for closing down of hydropower facilities and/or lowering of reservoir levels in order to do necessary upgrading and rehabilitation of dams and spillways.

A significant increase in the design flood values for dams may be the result of climate change, and this will further lead to insufficient spillway capacity and/or freeboard at many dams. Even without climate change, floods larger than the design flood are likely to occur. Reasons for this may be for example short time series or incomplete time series used for design flood estimation. The challenge of floods exceeding the design flood is therefore relevant to discuss in any case, as well as the possibility of experiencing more extreme weather and more frequently occurring floods than what we have experienced so far. Typical problems related to operation of dams during floods and recommendations for handling large floods and more frequently occurring floods are given by Kjellesvig & Midttømme (2001) and Kjellesvig (2002). The main conclusion is simple; upgrade the dams and spillways in order to provide safe bypass of floods exceeding the design flood. Redundancy in spillway systems is also promoted as a safeguard against flood related damages and any following consequences, along with good monitoring systems for early detection of adverse conditions. Another possibility would be to lower the HRWL in order to increase the freeboard, and thereby be able to store more floodwater in the reservoir. A simple solution to the problem of increasing design flood values is always to add extra safety margins when a dam is upgraded in the future as recommended by Bergström (2003) in a recent seminar focussing on climate change within in the hydropower sector. The challenge is probably to persuade the dam owners to select a more expensive solution than required today, even though this may be a sensible and perhaps also economic solution in the long run.

As mentioned above, floods cause an extra strain on dams and spillways, and in some cases the utmost consequence of a flood is a dam failure. A recent example from Norway is the failure of Nervatn Dam in Norway in January 2002. 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 20m 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). The failure of Nervatn Dam can not be assigned to climate changes directly, but the incident is a reminder of the fact that dams may be more vulnerable to floods, and effects of floods, in the future.

The probability of experiencing more ice-related problems in the future is also of special interest to Norwegian dams. Changes in temperatures may influence on the probability of “ordinary” floods and the more rarely occurring glacier lake outburst floods (GLOFs; also denoted jøkulhlaups) in glacier dominated catchments, as well as on other ice-problems such as icings/aufeis and ice-jams. A recent glacier lake outburst flood at Blåmannsisen glacier in northern Norway is believed to be a result of climate changes (Engeset 2001). The flood 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. The flood at Blåmannsisen resulted in a 2.5 m increase in the water level in the Sisovatn reservoir, corresponding to a 40 millions 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. Due to the low reservoir level prior to the flood, the Sisovatn Dam and downstream areas were not affected (Josefsen 2001). An interesting point in the case of Sisovatn is that a glacier lake outburst flood from Blåmannsisen had not been considered a probable exceptional load on the Sisovatn Dam in the most recent safety reassessment. The consultant performing the safety reassessment of the dam had probably not been made aware of the possibility, whereas the hydrologists performing glaciological investigations had foreseen this possibility several years in advance (Pedersen 2003).

CONCLUSION

It is difficult to conclude on how climate change will affect the safety of our dams in the next few decades, even though some scenarios have been pointed out as more probable than other scenarios by the researchers. The key parameter with respect to dams is the design flood, but the frequency of smaller floods is also of interest. Given the most probable scenarios, we should be prepared for more extreme weather and larger and more frequently occurring floods. The result will probably be an increased need for upgrading and rehabilitation of dams. As a regulator on dam safety, NVE will continue to evaluate the results from the climate change research. Further studies on climate change effects in Norway will naturally be of special interest in this context, as well as other research related to dam safety. The current approach to climate change with respect to dam safety is to evaluate actual changes in the data series used for flood estimation, i.e. to trigger a reaction to any observed changes in the climate (belated wisdom). The guideline on flood estimation points out that flood estimations must be classified with respect to uncertainty based on an evaluation of available data. This classification of the flood estimations is meant to be a support for NVE in the further evaluation of any structural or non-structural measures for the dams. The guideline on flood estimation also recommends sensitivity analyses. The latter can be helpful in order to evaluate possible consequences to dams of specific climate scenarios.

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