The 1995 flood in southeastern Norway. Operational forecasting, warning and monitoring of a 200-year flood

DAN LUNDQUIST
Glommens and Laagens Water Management Association, Drammensveien 30, PO Box 2903 Solli, N-0230 Oslo, Norway

KJELL REPP
Norwegian Water Resources and Energy Administration, Middelthunsgt. 29, PO Box 5091 Majorstua, N-0301 Oslo, Norway

Abstract In the spring 1995 Norway experienced the highest flood during the last 200 years. The experience showed the need for a thorough evaluation of the national streamflow and flood warning system and concluded that there is a potential for improvement of the forecasts. The Norwegian Water Resources and Energy Administration, which is responsible for the national flood forecasting system has to cooperate closely with the regional water management associations, which possess the detailed knowledge of the water courses. The damage done by the 1995 flood was reduced, due to careful operation of the reservoirs in the basin.

INTRODUCTION

The topography as well as the climate of Norway is highly varied. The western coast of Norway, being exposed to the westerly low pressure systems, receives up to 6000 mm of precipitation annually, while the precipitation in the driest parts of eastern Norway seldom exceed 300 mm year\(^{-1}\). Flash floods occur occasionally along the western coast, while the highest historical floods causing major damage have been experienced in the eastern areas, particularly in the Glomma River basin (Fig. 1).

A huge flood, causing a lot of damage and loss of many lives, was reported in 1789, while more recent floods occurred in 1966, 1967, and in 1987. For the 1995 flood, preliminary flood frequency analyses indicate return intervals varying from 50 to 200 years, depending on the location within the basin. An example of a historical time series of flood levels is shown in Fig. 2.

NATIONAL FLOOD FORECASTING IN NORWAY

Modern flood forecasting started in Norway after the damaging flood in the Glomma River in 1967. The forecasting, which was only based on observations of the snow cover and snow depth and a simple regression model, was limited to the middle and lower parts of the Glomma River basin, which covers approximately 40 000 km\(^2\). After a new flood in 1987, which covered larger areas of southern Norway, it was decided to establish a flood forecasting system covering the whole country. The system was developed during 1988, and from 1989 a continuous streamflow
forecasting and flood warning service has been operated by the Norwegian Water Resources and Energy Administration (NVE).

The service is based on 7-day quantitative temperature and precipitation forecasts from the Norwegian Meteorological Institute, which are inputs to a precipitation-runoff model, the HBV model (Fig. 3), which has been calibrated for 19 different catchments throughout Norway.

These catchments serve as indicators for different geographical and climatological regions in Norway. Water levels from 50 hydrometric stations are automatically transmitted to NVE every morning, and 20 additional stations are accessible by telephone at any time to get the real-time water level. All water levels are automatically converted to discharges. Additional information is obtained in real-time from five snow pillows (water equivalent) distributed throughout the southern Norway. Information on snow depths is also obtained from some hydropower companies, which carry out snow measurements regularly. AVHRR satellite data are used to assess the snow cover whenever possible, and these data are analysed to give
Fig. 2 Historical flood levels in Lake Mjøsa since 1789.

The percentage snow cover in height intervals of 100 m for any part of the country. There is, however, no automatic link between these data and the snow reservoir in the HBV model.

Based on the above information, the 19 HBV models are run every day, and qualitative forecasts are during normal runoff conditions distributed twice a week by telefax to NVE’s five regional offices, the Directorate for Civil Defence and Emergency Planning, the Ministry of Industry and Energy, the Ministry of Justice, the Norwegian Meteorological Institute, hydropower companies, the Norwegian
Broadcasting Corporation and the Norwegian News Agency, and on Text TV. During floods the forecasts and warnings are published more frequently, dependent on the actual situation. Besides the regular forecasts, press releases are usually sent out in late winter/early spring, describing the snow situation and possible scenarios of flood risk during the subsequent snow melt season.

Limited resources have not made it possible for NVE to carry out quantitative water level forecasting. Besides limitations of resources, most of the larger rivers are regulated, and water levels will to a large degree depend on the operation of the reservoirs. At present it is not possible for NVE to fully utilize this information, even if received from the various operators of water reservoirs.

**RUNOFF FORECASTING FOR HYDROPOWER PURPOSES**

Most hydropower producers in Norway have implemented some system of forecasting procedures, with the purpose of optimizing the hydropower production from natural runoff and from water stored in the reservoirs. In Scandinavia, the Swedish HBV model is the most often used rainfall–runoff model for such forecasting. At Glommens and Laagens Water Management Association, GLB, such HBV models have been calibrated for simulation of the hydrological response of 34 individual subcatchments. These catchment models are tied together by a complete basin model, which routes the calculated local discharges through the reservoirs and further down the main river to the sea. The concept includes automatic updating of the HBV models by use of Kalman filtering techniques.

This is a complete river basin model, which also includes physical limitations on the operation of the 26 reservoirs and water-course diversions. It is a fast and effective tool for evaluation of the consequences of a particular reservoir operation on any of the 44 power stations in the basin. It can, of course, also be used for analysing the effect of changes in the natural runoff from a particular subcatchment on the river discharges further downstream.

In spite of the described advantages, one should, however, not forget that this model is mainly intended and calibrated for use under more normal conditions than experienced during the flood of 1995. It is not primarily a flood forecasting tool but an aid for economical optimization of the hydropower production. On the other hand, forecasting for both flood-damage control and hydropower production usually aims at minimizing the unintended loss of flood water from the reservoirs, thereby reducing the flood peaks and the bypassing of discharges outside the hydropower stations.

**FORECASTING OF THE 1995 FLOOD**

At the end of April 1995, snow storage in the river basins of Glomma and Laagen had accumulated to 130–150% of normal. In the beginning of May, temperatures rose and snowmelt slowly began. After one week, however, temperatures fell again and snowmelt stopped. Fresh snow even fell at altitudes as low as 500 m and the weather forecasts indicated low temperatures for at least one further week. On this
basis GLB already in the beginning of May predicted possible high water levels in June to cause damage around Lake Mjøsa, Norway's largest lake. Such predictions, however, are not the same as forecasts, since they are based on quantitative weather forecasts for only one week, and thereafter on a statistical analysis of historical data. They represent a limited selection out of a large number of possible scenarios. This explains the rather large variation of water levels predicted for Lake Mjøsa at the beginning of June (Fig. 4).

On May 22 temperatures in the whole catchment started to rise again. They increased by as much as 10°C during six days, and snowmelt was rapidly initiated up to altitudes of 1000 m. Melt intensities in parts of the river basin reached levels around 20 mm per day for several days. The meteorological situation during this week was characterized by an almost stagnant frontal zone, with locally high precipitation intensities, and at noon on 31 May the Norwegian Meteorological Office issued a warning of extreme precipitation. A few days later, on 2 June, the combination of simultaneous snowmelt and precipitation in the upper parts of the basin produced a sharp flood peak. Flood forecasts during these days were sometimes quite uncertain, since they were depending on the precision of the highly variable meteorological forecasts.

Other factors influencing the quality of the flood forecasts are the goodness of the hydrological models calculating runoff from precipitation and snowmelt, and the hydraulic models describing the routing of the flood peak down the river and through lakes and reservoirs, like Lakes Mjøsa and Øyeren. During an extreme flood, like the one of 1995, effects not considered by the models may also occur. Examples of these kinds of effects are the breakdown of dikes, which withdraw large volumes of water from the river, when they could have made large damage further downstream. After the peak of the flood some of this water will gradually be returned to the river again.
THE EFFECT OF THE RESERVOIRS

Due to the generally large amount of snow in the river basin, GLB already on 7 April asked NVE for permission for extraordinary pre-release of water from one reservoir, Lake Osen, to prepare space for the expected snowmelt volumes (NVE is the national water management authority granting water rights). Later, on 8 May, GLB asked for another extraordinary permission to pre-release water from Lake Mjøsa, Norway's largest lake. The onset of snowmelt was now significantly delayed and higher snowmelt intensities than normal could, therefore, be expected. The possibility of simultaneous snowmelt contributions from the lowlands and the mountains also increased every day. During the coming weeks, GLB and NVE were in frequent contact concerning the growing danger of an extreme flood. Several new permissions for extraordinary regulation had to be granted. In many reservoirs the release of water was maintained at high levels to ensure the flood dampening capacity of the reservoirs. At the most critical stage around the flood peak, this was a continuous act of balancing. The strategy was to release water at a high level until the flood peak was expected, and then to decrease releases to a minimum, thereby cutting off the peak. Because the flood peak itself was a combination of snowmelt and precipitation, decisions had to rely heavily on meteorological forecasts.

The combined result of the pre-releases and the other reservoir regulation during the most critical days was a significant downstream reduction of the flood peak. The effect of the reservoirs was unexpectedly large, considering the fact that the total degree of regulation of the river basin is only 16%; that is 16% of the mean annual runoff within the basin can be stored in the available reservoirs.

At Elverum in the Østerdalen Valley, runoff was reduced by approximately 20%, and at Losna in the Gudbrandsdalen Valley by approximately 15%. Without the effect of the reservoirs, the flood at Elverum would have reached levels above the extreme flood of 1789 (Fig. 5).

![Fig. 5 The 1995 flood at Elverum.](image-url)
The 1995 flood in southeastern Norway

As a consequence of the reduction of runoff from the upper parts of the basin, the water levels in Lake Mjøsa and Lake Øyeren also were significantly reduced. For Lake Øyeren the combined effect of the regulations upstream, excavations made at the natural outlet after the 1967 flood, the reopening of two bypass tunnels, and the increased capacity of the power station, was a reduction of the water level with as much as 4 m (Fig. 6).

**LESSONS LEARNT AND POTENTIAL FOR IMPROVEMENT**

Just prior to the 1995 flood, a thorough external evaluation of the national flood forecasting system was initiated, which intended to look at the cost–benefit ratio of the forecasts and warnings, and propose improvements in accordance with the cost–benefit analysis. The evaluation was extended to include the experiences from the 1995 flood, and concluded that the national flood forecasting and warning system can be highly improved, provided that the necessary funds and resources are made available, while minor improvements can be achieved with the present resources.

With regard to erroneous and diverging forecasts, the report concludes that those errors are usually caused by the following factors as the most important ones:

* Discharge data may be inaccurate because of unreliable rating curves at flood stages.
* Quantitative precipitation and temperature forecasts are inaccurate.
* Initial snow storage in the HBV model is inaccurate.
* Lag time of the rivers has been over- or underestimated.
* Actual operation of water reservoirs is unknown a long time in advance.
* Calibration of the precipitation–runoff models is insufficient.
* Magnitude of water storage (including effect of flood levee breaks) along the river during flooding is unknown.

This conclusion is supported by the preliminary report by the official Commission on Flood Protection Measures, which was appointed by the Norwegian Government in July 1995, with the aim to evaluate possible improvements of disaster prevention related to floods.

The improvements suggested by the Commission can be classified as follows:
* Technical and “scientific” improvements, including refining of meteorological and hydrological models and increasing the quality of the data input to the models.
* Organizational improvements, including closer cooperation between NVE and other governmental agencies as well as with private agencies and organizations, e.g. hydropower companies and regional water management associations.
* Improvements in the distribution system of the forecasts and warnings.

The flood of 1995 clearly shows that the regional Water Management Association has an important role to play during extreme floods and that it has a large responsibility for damage prevention. The flood also showed that optimal utilization of reservoirs often depends on the possibilities of permitting deviations from normal regulation procedures. Close cooperation between the reservoir owners and the authorities is, therefore, very important. The primary goal has to be overall maximum damage reduction, without consideration of corporate prestige and interests. The flood of 1995 also showed that it often will be the regional Water Management Association (in the 1995 case: GLB) that has the best knowledge about the river basin and the possibilities for damage reduction.

The Commission concluded that “quantitative forecasting in regulated rivers should be performed as a cooperation between the reservoir owner and the authorities”. It also pointed out that only one forecast should be issued during extreme floods, to avoid different and confusing bases for the planning of actions to be taken.

Regarding the effect of reservoirs, the Commission has looked at possible new regulations in the Glomma River basin which could increase the flood reduction potential, since the present degree of regulation is only 16%.