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New Procedures for Flood Estimation in Norway

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The paper describes the development of new procedures for flood estimation for dam design in Norway. It summarizes the regulations and recommendations for flood calculations set forth by "The Norwegian Regulations for Planning, Construction and Operation of Dams" and the recent guidelines issued by the Hydrological Department of The Directorate of Water Resources.

Introduction

In Norway, as in most other countries, the traditional approach on flood estimation for dam design has been by use of empirical formulas, based on enveloping curves. The set of formulas known as Søgnens formulas (Søgnen 1942) gave regional estimates of flood values from specific flow and catchment parameters. The estimates were probably never intended to give maximum possible flood values, but to give a "reasonably high" flood. Dam safety was catered for by engineering safety factors.

As the amount of data available grew, and use of flood frequency spread, it became increasingly evident that the empirical formulas gave non-consistent flood estimates. An investigation concluded that the return period of the flood estimates varied from 300 to several thousand years. Together with varying practice in choosing safety factors this resulted in large variations in final safety level.

In 1976 a governmental committee was given the mandate to work out comprehensive regulations for dam design. The committee gave its recommendations in 1979 and the regulations were made effective from Jan. 1, 1981 (NVE 1981).

The regulations comprise planning requirements, site management, initial filling restrictions, load estimates, flood calculations, spillway design and dam design for rock fill and concrete dams. They are devided in two parts; mandatory regulations and recommendations. A translation in English is available (NVE 1986).

In the work with the regulations, the hydrological investigations were aimed at bringing the procedures of flood estimation in line with internationally accepted methods, as developed during the sixties and seventies (NERC 1975; Sokolov Rantz and Roche 1976).

In parallel with the work of the committee, methods for flood estimation were developed. Comparison of different distribution functions for flood frequency analysis was reported by Wingård (1977), and guidelines for flood frequency analysis was given by Wingård *et al.* (1978). After this, the development work has been concentrated on methods for probable maximum flood (PMF) estimation, and estimation of inflow flood volumes. The practices that have emerged through development work and actual flood calculations for dam design are summed up in recently issued guidelines (Vassdragsdirektoratet 1986).

Regulations

The regulations apply to permanent dams approved after Jan. 1, 1981, with dam height of more than 4 m or dammed reservoir volume of more than 0.5 hm3. They also apply to revisions of older dams, and in practice the regulations also set the standards for evaluation of the safety of existing dams. The approving and controlling authority is the the Water Works Supervision Divison at the Directorate of Water Resources.

In the general comments on flood calculations, the following directions are set forth:

"Hydrological calculations shall be made to determine the design inflow flood, design outflow flood, probable maximum inflow flood and probable maximum outflow flood, with associated water levels in the reservoir."

"The aim of the flood calculations shall be to determine the necessary data for the design of the dam and the outlet works, and shall also form the basis for determining the capacity, characteristics and operation of the spillways."

"The design flood shall be used in the calculations of water levels and discharges that form the basis for the design of the spillway and outlet works, whereas the probable maximum inflow flood shall form the basis for calculations to check the safety of the dam against failure."

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"It shall be demonstrated that the natural flood conditions in the river downstream of the dam will not be impaired, ..."

It is worth noting that the regulations define two standard floods: probable maximum flood and design flood. The design flood is defined as the inflow flood with a return period of 1,000 years. On the other hand, the regulations do not classify dams and dam design criteria by dambreak consequences.

The main principles for flood calculations are then:

- the design inflow flood sets the standards for normal spillway operation
- the probable maximum inflow flood sets the standards for dam safety
- the design flood has a return period of 1,000 year, and accordingly has to be determined by some type of frequency analysis
- PMF is calculated on the basis of probable maximum precipitation values and snowmelt estimates
- outflow floods and maximum reservoir levels are determined by routing the inflow flood through the reservoir
- the reservoir levels and the outflow floods are thus dependent on spillway design
- the spillway should be designed to handle the design flood without increasing the natural floods on more frequent levels

The design flood and the probable maximum flood standards applies to all dams covered by the regulations. But while most concrete dams will withstand overtopping during a short flood period, rockfill dams can not be allowed to overtop. The consequence of this is that the PMF in practice becomes the design standard for spillways on rockfill dams.

The dam regulations recommend use of free flowing ogee spillways whenever possible. As the capacity of such spillways increase quickly with increased reservoir levels, dams with this type of spillways are less sensitive to variations in the dimensioning flood than dams with closed conduits. Free flowing, ungated spillways also have operational advantages.

Flood Duration

When the water level in the reservoir is allowed to rise during a flood, through deliberate regulation or by the restricted capacity of a fixed spillway, the outflow flood will be damped compared to the inflow flood. In that case not only the peak magnitude of the inflow flood, but also the volume and temporal distribution of the inflow flood affect the magnitude of the outflow flood and the corresponding peak reservoir level.

In a small reservoir, the flood damping effect of the reservoir above the spillway crest may be negligible, and the outflow flood peak approximately equal to the inflow flood peak. Then it is only necessary to estimate the peak magnitude of the inflow flood. For a large reservoir, on the other hand, it may take several days of high inflow to raise the reservoir to flooding levels, and all rapid variations of the inflow hydrograph are smoothened out. In this case, the inflow flood volumes for long durations are important, while the peak magnitude of the inflow flood will be of minor interest.

The highest peak flows and the flood volumes for longer durations may belong to entirely different flood populations, for instance autumn rain floods and spring melt floods, and might never combine.

To give some guidance on what durations deserve most close investigation, we have adopted what could be termed "reservoir critical duration" as a time "constant" describing the damping effect of a reservoir with an ogee spillway. This parameter is (Sælthun 1985)

$$Tm \equiv 480\ A\ Qi^{-\frac{1}{3}}\ (CB)^{-\frac{2}{3}} \qquad \text{(hours)}$$

for a reservoir with surface area of A km^2 at flood stage, spillway width of B (m), and discharge coefficient C (approx. 2). Qi (m^3/s) is the mean inflow magnitude over Tm, but due to the low sensitivity of Tm to Qi, four times the mean annual flood of 24 hrs duration can be used as an estimate of Qi in most cases of extreme flood calculation.

Tm is the time it takes for the reservoir outflow to rise to 80% of a constant inflow of Qi, when starting at spillway crest level.

Design Flood Calculations

Flood Frequency Analysis

As design inflow flood is defined as a flood with a return period of one thousand years, it has to be established by some kind of flood frequency analysis. Several theoretical distribution functions has been tested on annual floods in Norwegian rivers, and three-parameter log Pearson has been found to generally give the best fit (Wingård 1977, Wingård *et al.* 1978). Practice, both in Norway and internationally (Cunnane 1985) has shown that in particular three-parameter distributions are very sensitive to outlying events with the commonly used parameter estimation methods.

The guidelines (Vassdragsdirektoratet 1986) therefore recommend comparison of several distributions (two- and three-parameter) when estimating design flood magnitude, and careful consideration of the influence of outliers in the data set.

Based on the observation record length the following recommendations are given (QM denotes the mean annual flood and $Q1000$ the design inflow flood):

>50 yrs:	*QM* is estimated from observed series and *Q*1000/*QM* from two or three-parameter distributions on observed series
30-50 yrs:	*QM* is estimated from observed series and *Q*1000/*QM* from two-parameter distributions
10-50 yrs:	*QM* is estimated from observed series and *Q*1000/*QM* from other long series in the region, alternatively on series extended by rainfall/runoff models.
<10 yrs:	*QM* is estimated by correlation on other series in the area or by catchment parameter formulas (Wingård *et al.* 1978). *Q*1000/*QM* as above.
No obs.:	*QM* is estimated by catchment parameter formulas or comparison with similiar catchments in the vicinity. *Q*1000/*QM* as above.

Generally, the *Q*1000/*QM* growth factors should be compared with results from catchments in the vicinity, and with the growth curves of Wingård *et al.* (1978). Experience seems to indicate that those regional growth curves are somewhat on the high side. The same has been said about the regional flood growth curves of the British flood study, which are estimated by the same procedures (Hosking *et. al.* 1985).

Spring and Autumn Floods

The floods in most Norwegian rivers stem from two populations, spring snowmelt floods and rain floods. These floods can be combined, but in many cases it is appropriate to consider them as belonging to two flood regimes and treat them separately; the perennial spring flood with high volume and high *QM*, but moderate growth curves; and the autumn floods, of shorter durations and high intensity, and steeper growth curves.

The predominant flood season was mapped by Wingård *et al.* (1978).

Using Precipitation and Rainfall/Runoff Models

An alternative approach is to calculate the design flood from an estimate of the precipitation event with 1,000 year return period by an appropriate rainfall/runoff model. Such rainfall estimates are standard analyses at the Norwegian Meteorological Institute (Førland and Iden 1984). There are several points in favour of making the frequency analysis on precipitation rather than runoff. The uncertainty increases more by magnitude for runoff than for precipitation, and precipitation is probably easier to regionalize and interpolate between observation points than runoff.

The problems in starting out with a thousand-year precipitation event are that it is very difficult to combine this precipitation event with proper choices of initial catchment moisture state and snowmelt/snow accumulation to output a runoff event with one thousand-year return period. This procedure is therefore only recommended for small catchments with poor observation base, and for control calculations.

Estimating the Peak Flow

In Norway, as in most other countries, the gross amount of available runoff data is daily data. It is therefore not straightforward to estimate a peak flow value for the design flood hydrograph. Recently a lot of recorded stage data has been digitized as a data base for analyses that need fine time resolution. These data can be used directly for flood frequency analysis, but the observation period is usually quite short, as most stations have been equipped by stage recorders during the last couple of decades. Preliminary investigations seem to indicate that the growth curves of the peak flow and the daily flow are quite similiar. The *QM* value for the peak flow could thus be determined from observations and the growth curve from daily values.

Attempts to estimate the ratio between peak flow and corresponding daily flow from individual flood events are not likely to yield good results, due to very large variations between events.

Design Flood Hydrograph

To calculate the design outflow peak flow and maximum reservoir stage, the design inflow flood is routed through the reservoir. To do this it is necessary to determine a inflow flood hydrograph. It is recommended to do this by scaling an observed flood event. The scaling is done by scaling the peak flow to the estimated maximum flow, and then by adjusting the time scale to obtain correct volume over the reservoir critical duration. To avoid unrealistic distortion of the flood hydrograph, the ratio of the peak flow to mean flow on critical duration should not be too different for the model flood and the design flood.

Flood Routing

The design parameters; design outflow flood and design reservoir level are obtained by routing the design inflow flood through the reservoir, given the reservoir curve and the discharge characteristics of the spillway. The routing conditions are normally:

- initial reservoir stage is set to highest regulated level (normal water level, NWL)
- interbasin transfers in the most unfavourable state, i.e. transfers to the catchment are considered open and transfers out closed.

The design outflow flood and the design reservoir level are dependent on the dimensions and discharge characteristics of the spillway. In principle, the spillway design will also affect the design inflow flood through the *Tm* value, but this does usually not pose any practical problems. The only way to overcome this would be to use a design inflow flood containing the *Q*1000 value for all durations. The return period of this "combined" flood would be significantly higher than a thousand years.

Probable Maximum Flood

The probable maximum flood calculations are based on estimates of probable maximum precipitation (PMP) given by the Norwegian Meteorological Institute, converted to runoff through a rainfall/runoff model. Internationally, the unit hydrograph method has been much used for this purpose, but the baseflow separation process poses difficulties in the calibration and application of this model type. In the Norwegian studies an adaption of the HBV model has been used (Andersen *et al.* 1983).

Probable Maximum Precipitation

The procedure for maximum precipitation estimation used by the Norwegian Meteorological Institute (Førland 1984) is based on growth curves and mapping of daily precipitation with five year return period. The growth curves are based on the UK studies (NERC 1975), but controlled against Norwegian data. In the NERC investigations, the PMP level of the growth curves is set by envelopes on the large amount of British precipitation data, and was checked against large observed UK events, augmented by maximized atmospheric moisture content.

Areal reduction factors, to account for the effect of time and space variations in precipitation patterns, have also been adopted from the UK flood studies. These reduction factors are statistical averages for fixed areas, relating to precipitation events of two to five year return period (Bell 1976). The reduction factors are dependent on precipitation duration, and the reductions are largest for short durations.

The justification for applying the UK results to such a large extent is that the precipitation regimes are not very different in the British Isles and in Norway; and UK benefits from an exceptionally dense network of precipitation stations with long observation period. The Norwegian network has far less observations, and due to topography it is very difficult to make analysis of the variation pattern in space.

The PMP values have been compared to the highest observed rainfall values (Førland 1984). For most regions the highest observed values are in the order of 40 to 60% of the PMP values.

Temporal Precipitation Distribution

Investigations do not reveal any typical temporal storm profile for large precipitation events. In accordance with WMO recommendations (WMO 1973) and the flood studies report, a close to symmetrical distribution has been chosen for durations up to two days. For larger durations, the precipitation will usually be caused by several consecutive events, and it is recommended to base the PMP profile on scaled observed series.

Critical Season

In most parts of Norway the highest precipitation values are experienced in autumn and winter. In inland regions summer may give the highest events, especially for short durations. The spring values are the lowest. On the other hand, the spring snow melt may produce the necessary extra water to make the spring PMP critical for systems that need high flood volumes and long durations to rise to a high outflow flood. Except in coastal areas there is always a winter season without floods.

By considering the precipitation and runoff regimes, it is usually possible to define a season that would be critical to the system in the sense that PMF is most likely to occur in that season. In most cases it is late autumn, with combined rainfall and snow melt. For large reservoirs and catchments it might be spring melt with rainfall, and for small systems summer situations. PMP values can be specified to season by the Norwegian Meteorological Institute (Førland 1984).

Snow Melt

In may cases combination of PMP and snow melt forms the input to the rainfall/runoff model. The guidelines for snow melt estimation are:

Spring floods – Snow melt and runoff are simulated through the entire snowmelt season as follows:

- initial snow cover is set to the highest observed or corresponding to a return period of at least 30 years
- the temperature development is set to the lowest observed to get a late spring flood
- then the temperature is set to the highest observed for the actual season
- when the snow covered area start decreasing, temperature is dropped to the highest observed during precipitation for the actual season in the lapse of one day, and the seasonal PMP is applied

Autumn floods – Snow melt is only considered during the PMP event, and temperature is set to the highest observed during rainfall after the normal date for snow cover in the catchment.

Snow melt is calculated by the hydrological model, which uses altitude zones and temperature index snow melt estimation. The following temperature indexes are recommended (mm/deg C/24 h):

	Dense forest	Open forest	Highland	Glaciers
No rainfall:	1.5	2.0	2.5	3.5
Rainfall:	3.0	4.0	5.0	7.0

Rainfall/Runoff Model

As mentioned above the rainfall/runoff model used is a simplified HBV model. In fact, it is very close to a complete HBV-3 model, but with many parameters preset to standard values. The three parameters that control the dynamical response of the model; two response coefficients and one threshold value are determined by calibration or by standard formulas on topographic parameters (Andersen *et al.* 1983).

The model is integrated in a general, portable Fortran 77 program package for flood calculations (Andersen 1984). In addition to the model, the program has capabilities for data series manipulation, inflow computation, reservoir and river routing, and hydrograph adjustment.

Calculation of PMF

Given areal PMP values with temporal distribution, and temperature series in case of snow melt, and after determination of model parameters, calculation of the inflow probable maximum flood is straightforward. The initial moisture content of the catchment is normally set to saturation.

The inflow PMF is then routed through the reservoir, as in the case of the design flood, and under the same conditions, giving a maximum reservoir level and a maximum outflow.

More than One Reservoir

Problems arise when design flood and PMF are to be computed for reservoirs downstream other reservoirs. The flood calculations should take into account the advantageous effect of the timing difference of the outflow flood from the upstream reservoir and the local inflow flood, and of the total areal reduction. Otherwise the flood estimates would increase unrealistically down the river. We could even be confronted with situations where adding a reservoir upstream an existing reservoir would raise the flood estimates for the existing reservoir, even if the new reservoir is designed to reduce the natural floods.

The general rule is therefore not to start out the flood calculations with the flood estimates of the upstream reservoir, but to estimate the inflow flood for the total catchment, and then route the flood through the reservoirs and the watercourses. The routing only produces the design or probable maximum flood for the downstream reservoir.

Further Development

The greatest uncertainties in the flood calculation procedures seem to be connected to the application of the areal reduction factor for large catchments. The commonly used areal reduction curves are based on fixed area analysis and rainfall events of moderate return period. Storm centered curves should be expected to be more appropriate for PMF calculations, and such curves tend to fall off more quickly than the NERC curves (Bell 1976). The difference may be significant for large catchments. For large catchments the travel time and direction of the storm might influence the PMF calculations.

Further comparisons of estimates of PMP by statistical methods and maximizing procedures would be of great interest.

These aspects are under investigation in an ongoing project at the Norwegian Meteorological Institute.

New development on regionalization of hydrologic variables and on flood distributions will probably give us better methods for flood frequency analysis within a few years. We are following the research by professor Lars Gottschalk at the University of Oslo and by the European flood studies group at the Institute of Hydrology, Wallingford, with great interest.

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